

Conceptual Methodology for the Design of Dairy Processes

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Abstract

A considerable amount of literature exists regarding design strategies and methodologies for large scale chemical engineering processes. However, the majority of the effort has focussed on petrochemical industries. Consequently, design strategies have been tailored to the specific requirements of these industries. Process design for food industries presents a number of unique challenges and problems, many of which cannot be addressed by existing petrochemical-based design methods. The principles of operation of most dairy processes are well known, but procedures for their design are not published in open literature. Large scale dairy design is often a mixture of heuristic and ad hoc methods, relying heavily on the experience of the designer.

This thesis compares petrochemical and dairy processes, and considers points of similarity and difference. It was identified that petrochemical processes were typically centred around reactions, whilst dairy processes were mainly focused on separation and blending of selected components. For this reason, it was determined that petrochemical methodologies were not particularly relevant to the dairy process design.

This study presents a new conceptual methodology for developing and assessing dairy process flowsheets. The methodology considers possibilities for integration of material, energy, water, time and the environment, between and within processes used in the dairy industry. It also considers opportunities and requirements for integration and provides the fundamental process understanding required when developing the new conceptual design methodology. The methodology is presented using four case studies covering small, medium and large scale processing operations. These case studies illustrate that the new methodology makes it possible to develop process designs in a more structured manner. More importantly, it enables integration opportunities for all process and product lines, particularly for medium and large-scale operations where a structured approach is required to systematically identify and assess integration possibilities.

This thesis lays the foundation for dairy process design by introducing the evolution of conceptual process synthesis using a top-down framework to complement subsequent detailed design when required. This methodology represents a significant improvement over the current methods available for chemical process design in the dairy industry.

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1 Introduction

1.1 Overview of Design

Design is the focal point of chemical engineering practice, but is far more than the development of a set of specifications for a new chemical plant. Design is that creative activity through which engineers continuously improve the operation of facilities to create products that enhance the quality of life (Turton *et al.*, 1998). Design typically starts as an ill-posed problem to be resolved; the first activity is to establish the goals and tests, establish starting points and define the design space. For example, the purposes of chemical processes are to create the highest return on investment, in a safe and flexible process. Tests are used to evaluate and compare design alternatives before the final decision is made. There is also a need to define where to start the design, whether to base it on an existing one, or start from scratch. In addition, it is necessary to define the design space. The design space is defined as the set of all alternative process designs but it keeps changing as technological advances give more available alternatives (Westerberg *et al.*, 1997). The space of design alternatives is very large and continually changing (Laing & Fraga, 1997; Westerberg *et al.*, 1997). Design is difficult because problems tend to be open-ended; designers do not always have complete information and need to make complex decisions (Biegler *et al.*, 1997).

Design generally is initiated by ideas from almost anywhere. For example, a customer might need a material with properties not available in any product currently on the market or the company may want the engineers to come up with a process whereby the surplus feedstock the company is currently producing can be used (Biegler *et al.*, 1997).

There is a number of traditional process design methods available in the literature and most of them focused on the reactor as the first stage (Douglas, 1988; Smith, 1995; Wall *et al.*, 2000). Some of these traditional process design methods are examined for their applicability in dairy process design in Chapter 2.

1.2 Dairy Industry Background and Historical Dairy Process Design

Since European settlement, the New Zealand bush has given way to grass as feed for animals. Family cows produced milk for the settlers' families and the surplus was sold, initially as butter and later as liquid milk and cheese.

Until the 1960s, the cheese making throughout the world was a highly labour intensive art. Since then New Zealand scientists have contributed greatly to the understanding of the chemistry and biochemistry of the process, and through mechanisation have transformed cheese-making into a reliable and profitable industry.

As the scale of the industry increased, from cottage industry to medium and larger scale plants, a factor of economy appeared. Complex operations, product control, production capacity, and the need to scale up, all required the knowledge of chemical engineers. Waste minimisation also became an important issue.

Eventually it was recognised that many of the dairy industry's problems are unique and that other industries' solutions to apparently similar design problems might not work in this industry, or vice versa. Further the design needs vary from region to region.

The growth of milk production, industrial structures and processing operations have changed from chemical engineers providing a service to many small companies with a variety of problems, to in-house operations, where specialist engineers tackle the concerns of the industry as a whole. The production of dairy products is carried out on a variety of scales throughout the world. Design challenges and requirements differ depending on the scale of the operation.

Process integration is a relatively new area for engineering design methodology. Until recently, engineers developed conceptual process designs by experience and intuition without using methodology (Linnhoff *et al.*, 1994). Process integration is carefully considered in this study (see Chapter 6). Therefore, the design for this research will start with a household batch process, and from there move to a small scale process operation in the Andes of Peru (Pucyura), then to the medium scale on a small site in South America (Lima), and finally to the large scale process in New Zealand. The

research will identify opportunities in each case, according to the location of the process design and the raw milk capacity.

The chemical engineering design approach demands that the design of dairy processes includes all the disciplines of chemical engineering such as thermodynamics, physics, chemistry, thermal and mass transfer, and fluids. Science frequently needs to draw on biochemistry and microbiology, as well as purely chemical and physical aspects.

1.3 Attributes of Dairy Process Design

Milk provides a good model in the food industry because most of the requirements of dairy processing overlap with general food processing such as food safety, supply volume based processing, the enrichment or deployment of its composition, the tendency to depend on some off-the-shelf equipment. Therefore, the design methodology for the dairy process offers a good model case study to compare with other branches of food processing.

Chemical engineers want the process to be safe, flexible, operational, economical and environmentally friendly. The dairy industry has specific design demands of engineering and formality in engineering design as follows:

Food safety

- If not handled properly milk can present a potential high risk to human health because it provides an ideal environment for the growth of pathogenic organisms.
- There is pressure to deliver a product on time to avoid spoilage.

In the case of milk, meat, fruit and many vegetable raw materials, it is an absolute requirement that products reach the market in a safe condition (Sharma *et al.*, 2000). Under this circumstance it is desirable to select the formulation that provides market satisfaction while meeting product and process constraints, and fulfilling safety requirements.

The specific food safety requirements for dairy process design are systems that ensure the hygiene of both plant and product. Food safety and product hygiene require regular clean-in-place (CIP) which involves periodic shut-down of the equipment. Therefore, scheduling is needed to coordinate these requirements effectively.

Profit

The purpose of a design methodology for the dairy industry is to create the best return for farmers (shareholders) in the use of their land and investment, maximising long-term income and profit to shareholders. The design objective is to process the milk and maximise return to the farmer by selecting the right equipment and process options. A number of issues arise here including:

- Farmers must make a living from the land, producing milk or there is no raw material.
- Shareholders demand return on capital.
- The profit depends on the chosen product mix of the processes and on the demands of the market.
- There are reduced profit margins for some products, for example, for drinking milk.
- Cost of production depend on the capital cost of the plant, operating costs.
- Extra costs are involved because of the need for plant and product hygiene

Environment

Milk processing presents several challenges to the chemical engineer. Because the raw material is perishable, the milk can not be stockpiled, nor can it be dumped into the environment because of its high biological oxygen demand (BOD) (Bloore, 2001). This places great importance on timely processing and plant reliability.

- Pressures to reduce the environmental impact of milk processing are increasing.

- Chemical engineers want the process to be environmentally friendly.

Milk Supply

Dairy process design also needs to take into account complex biological feedstock-variability of the composition and physical properties of milk components. The seasonal variability of milk volumes on the processing operations is dictated by farmers, not customers, and this too is an important factor when considering design.

Many foods consist of a mixture of ingredients that must be blended together to meet product specifications. Levels of fat, protein, water and other ingredients are generally taken into account. Milk already has a mixture of those ingredients which makes it a nutritionally complete food.

1.4 Aims of This Work

This work aims to bring dairy design methodology up to the standards of chemical process design at a conceptual design level. A top down approach is employed to provide a framework for subsequent detailed design. The developed methodology considers different scales of dairy process operations.

The present study represents a timely and appropriate topic for evaluation in the light of the call for higher productivity and quality in the dairy process industry. Apart from examining how milk components resources may be better integrated to enhance the productivity levels in the dairy industry, the study is also a pioneering investigation into the conceptual methodology for the design of dairy processes. It draws together the available literature and study in the manufacturing industry and enhances the current understanding of dairy components for the dairy process industry.

In addition, this study will provide decision-makers and chemical engineers with a powerful tool in the design of a dairy process industry. A full appreciation of the importance of design methodologies and the factors which are pertinent for its successful application will potentially increase the efficiency and effectiveness of the dairy industry. For some dairy processing companies, it may even enhance their

competitive edge over others.

Many specific factors must be considered at the conceptual process design stage. No methodology currently exists for including these considerations in a conceptual process design; its development constitutes a significant research opportunity.

1.5 Outline of Thesis

Design methodologies for the chemical process industry are reviewed in Chapter 2. Several significant differences and their main design implications are described in Chapter 3.

Unit operations typically used and the relevant applications in the dairy industry are reviewed in Chapter 4. Chapter 5 examines the typical production methods for different products derived from milk in the dairy processes.

In Chapter 6, simplified examples of integration are identified, between and within processes in the same site and between sites. In Chapter 7 the synthesis methodology for dairy process flowsheets is presented. This may permit chemical engineers to develop a completely new approach to dairy process design. The physical, chemical and biological phenomena must be understood to translate opportunities shown on the different flowsheets into dairy process designs.

The challenges are to find relevant information, to recognise the key elements of that information, and to apply those elements of the manufacture of desired products into an integrated dairy process design method. The method developed is applied in four case studies. These case studies show the design and development of process design methodology.

The design methodology for the dairy process industry should ideally lead to innovative designs.

1.6 The Contribution of This Thesis

The methodology, although it is deceptively short, is the distilled product of many months of considerations, thoughts, synthesis and analysis of the design process. The development of the methodology required a wide knowledge of dairy products, dairy processes and design synthesis techniques. The methodology can generate a large number of potential design options, some of which are clearly impractical, but others challenge existing processes.

The first consideration can have a large number of potential design options. It is believed that this thesis will be a stepping stone to more creative thinking on how to design a dairy process. The main contribution of this thesis are:

- First known attempt of conceptual design of dairy processing or in factory food processing.
- Creation of a framework for describing processes in terms of design objectives and constraints rather than the more general “principles of” processes that often give no useful design information.
- Formalisation of most dairy processes in terms of design information.
- Distillation of product information to the essential information for a designer.
- Development of a methodology which uses the new concept of a key process from which to synthesise a flowsheet.

For an experienced dairy process designer, the context of the thesis may seem obvious. This is seen as an indication that this work has been successful in extracting the essentials of design from the vast resource of available information of the principles of dairy processing.

2 General Aspects of Process Design

2.1 Chemical Process Design

The development of an optimal design solution to a specified problem requires a significant amount of skill and effort from a designer. Chemical process design is especially challenging because the number of possible flowsheet solutions is often enormous. The identification, selection and development of the final flowsheet design from a large number of alternatives are most efficiently achieved using a consistent strategy.

A number of process design methodologies have been presented in the literature, developed mainly from the petrochemical industries. Such methods represent the obvious starting points for developing a conceptual design methodology for dairy processes.

However, as noted in the previous chapter, there are a number of constraints and requirements specific to food processing which are not encountered in the petrochemical industries. The first part of this chapter reviews the main process design philosophies and tools published in the literature. It provides general information on the heuristics and hierarchy of the principles in the design processes. The primary design requirements and constraints that exist in the dairy processing are then considered. Finally, the conclusions on the applicability of the various methodologies to conceptual dairy process design are presented. It is intended for this chapter to lay a foundation for developing a specific dairy process design methodology in the later chapters.

This thesis focuses on the design process itself, specifically looking at methodologies for generating optimal dairy processing flowsheets over a range of scales, from single cow farm milk production through to the largest international processing sites.

2.1.1 Process of Design

Process design is an ill-posed problem with multiple, conflicting goals; a process must deliver high levels of safety and efficiency at minimal capital cost. The final “optimal” solution will provide the best combination of compromises or decisions that satisfy the original project goals (Ray & Sneesby, 1998). To achieve this, the designer must first generate or identify a set of feasible candidate flowsheets. Once this is done, a ranking strategy is applied to determine the most suitable option from which to generate the final design. This is usually an evolutionary process which iterates between the generation and assessment of candidate flowsheets. Westerberg *et al.* (1997) stated, that “design methodologies” play an important role aspect during this process. However, companies today assign only a small percentage of the intellectual capital they have at their disposal for the purpose of design processes (Westerberg *et al.*, 1997). Given the cost of poor design decisions and the increasing complexity of process flowsheets, design methodologies are more important than ever.

Figure 2-1 shows how a company should ideally capture and use history to improve the design process and shows also information flow during the design process. Knowledge from previous projects is typically used as the starting point for developing candidate designs from the current project. For new processes, the designer may start with a “proto-typical” design developed during the research and development stage. Many new process designs are developed in response to market demand. These may be generated by the need to fulfil customer requirements or by the identification of new opportunities within existing processes. New design projects may be initiated by either research developments or changes in market requirements (Westerberg *et al.*, 1997). The market imposes volume, cost and quality objectives for a product, derived from the scale and nature of the customers’ use. The market thus influences the raw material selection, the choice of the process and the separation procedures used, as well as the scale of the operations (Scott *et al.*, 1992). For this reason, candidate flowsheets are checked with the lead up to “feed-forward” modifications and predicted market demand. Reviewing the project sometimes can lead to “feed-back” modifications (Westerberg *et al.*, 1997). Both “feed-forward” and “feed-back” mechanisms typically occur within a specific design process, hence they operate in a relatively short time frame. At the completion of the project, design experiences can be captured and use as the basis for learning and reuse in subsequent design processes.

However, this process is dependent on a company setting up a team to review its processes, establish generic policies and protocols for design, and capture the lessons learned. Such feed back mechanisms have long time delays, and rely on firms maintaining the systemic procedures for capturing and storing design experience during a project. In most companies, such information is typically scattered within the organisation or stored in unorganised forms, and consequently companies find it difficult to review and reuse the expertise developed in previous projects (Westerberg *et al.*, 1997). Given such difficulties maintaining the “corporate memory”, companies may also use published design methodologies to generate candidate flowsheet designs. When doing so, it is extremely important that the methodology used is relevant to the industry, otherwise candidate designs may not provide best solutions to the design brief.

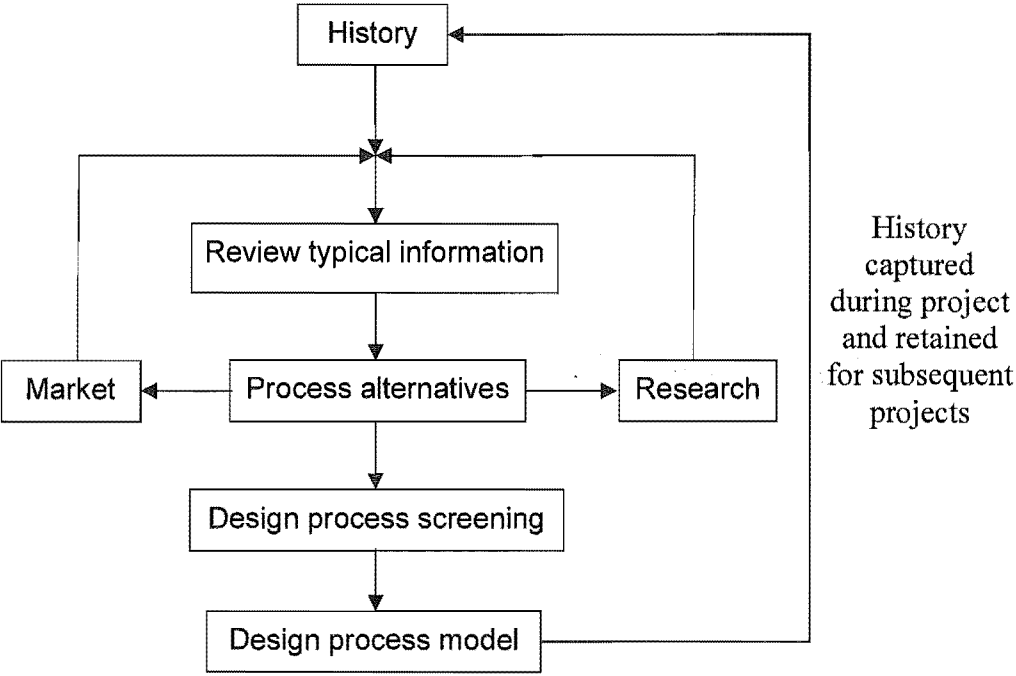


Figure 2-1 Phases of initial design acknowledging the history (based on Westerberg *et al.*, 1997).

For new processes, the design sequence is typically comprised of three stages (National Research Council *et al.*, 1988). In the first stage, new ideas are used to generate conceptual flowsheet designs. Process safety and environmental considerations are examined, and preliminary cost estimates are used to assess potential profitability of the

process. This stage is commonly referred to as “process synthesis” (Wai *et al.*, 1996; Biegler *et al.*, 1997; Turton *et al.*, 1998; Seider *et al.*, 1999; Steffens *et al.*, 1999, Steffens *et al.*, 2000b). In the second stage, one or more candidate flowsheets are selected, then all significant process details are specified and rigorous design calculations are carried out. The third and final stage involves detailed design, with the preparation of engineering drawings and an equipment list required for construction. Detailed process design is only carried out for the final “optimal” flowsheet selected for construction.

2.1.2 Conceptual Process Design

Conceptual process design has been defined by Nishida & Stephanopoulos (1981) as “an act of determining the optimal interconnection of processing units as well as the optimal type and design of the units within a process system”. Douglas (1988) added that “the goal of a conceptual design is to find the best process flowsheet (i.e. to select the process units and the interconnections among these units) and estimate the optimum design conditions”. Identifying a small set of candidate process flowsheets is a daunting task given the huge number of possible design concepts. For this reason, it is important to use a design methodology to efficiently generate and identify a set of realistic flowsheets that are likely to best fulfil the design brief.

However, Sinnott (2000) observes, “when considering possible ways of achieving the objective the designer will be constrained by many factors, which will narrow down the possible designs”. Through the conceptual design activities, the solutions are generated, selected and evaluated. This is not a trivial problem because there are often dozens or even hundreds of flowsheet possibilities to be assessed against the specified project requirements and constraints. The output produced by these activities is a design concept (Hales, 2000; Pahl & Beitz, 1996).

The use of design methodologies for generating process flowsheets, in conjunction with numerical methods for assessment and ranking, form a powerful base for conceptual process design (Linnhoff *et al.*, 1994). Design methodologies must enable the integration of a diverse range of process requirements and constraints including:

- Minimisation of capital,
- Low operating costs,

- Production flexibility,
- Reliability,
- Worker safety,
- Good controllability,
- Environmental protection and safety,
- Societal expectations.

Since many of these requirements are often contradictory, flowsheet development requires considerable compromise and trade-off (Grossman *et al.*, 1983). As an example, process controllability and flexibility can be improved through the provision of additional storage of the intermediate products. However, this may be contradictory to the capital cost minimisation objectives. For hazardous or perishable materials, increased inventory introduces additional environmental safety or health risks.

A design brief has similarities with a mathematical optimisation, having one or more objectives and being subject to various constraints. However, process design cannot be considered the same as scientific or mathematical problems which have a single solution or “correct answer”. This is primarily because the design problem is ill-defined, with missing or uncertain information, and constraints that cannot always be clearly quantified. It is the role of the designer to interpret the available information and specified constraints, in order to generate and select viable flowsheets. Many of the required decisions are made based on experience and heuristics. Such decisions require a degree of risk management, since it is necessary to assess the relative uncertainty in each piece of information (known or estimated), and its significance relative to the design objective(s) and constraints.

In many situations, the process requirements change over time from those initially specified in the design brief. Many petrochemical installations are expected to have a lifetime of decades. During this time it is likely that process will be modified as production, market and environmental demands change. This further complicates the design process, since possible changes in available technology, societal expectations and product specifications must somehow be interpreted by the designer. It is this requirement for designer input and judgement that distinguishes the design process from a numerical optimisation.

2.1.3 Chemical Engineering Process Design

In chemical engineering, the design objective is to create a new flowsheet or modify an existing one to be capable of manufacturing a desired chemical (Westerberg *et al.*, 1997). By rethinking the development activity and using qualitative process models, it is possible to identify efficient and innovative process options without excessive experimental data (Sadr-Kazemi *et al.*; 2000, Westerberg, 1999).

The design work required in the chemical manufacturing process is divided into two broad phases according to Sinnott (2000). The first phase design covers the steps from the initial selection of the process to be used. These include the selection, specification, design of equipment and the piping and instrumentation diagram (P&ID). Chemical engineers generally do this. The second phase covers the detailed mechanical design of the equipment. The structural design, civil design, electrical design, and the specification of the ancillary services responsibilities, will be carried out by other engineering disciplines.

Modern strategies for the design of chemical processes have been developed based on process design principles, and there has been an increasing introduction of computer resources involving spreadsheets, mathematical packages such as ASPEN PLUS, HYSYS, PRO-II, CHEM-CAD and FLOWTRAN, SPEEDUP, FORTRAN and simulators as more data is obtained in many cases; the material and energy balances are performed at least in part by these computer-aided process simulators (Seider *et al.*, 1999; Herman *et al.*, 1985). A strategy recommended by Seider *et al.* (1999) involves assembling the process operation in a specific order. Table 2.1 shows the organised process operation into a series of steps to eliminate the differences between streams in the process. The aim is to reduce these differences until the stream that leaves the last operation is identical to the required product. In chemical engineering literature, unit operations equipment such as evaporators, filters, and centrifuges are all involved in one or more of these eight basic operations (see Table 2.1) and the process synthesis step involves the selection of processing operations to convert the raw material to products Seider *et al.* (1999).

Table 2-1 Synthesis steps and the basic process operations (arranged from Seider *et al.*, 1999).

Synthesis step	Basic process operations
1. Eliminate differences in molecular types	1. Chemical reaction
2. Distribute the chemicals by matching sources and sinks	2. Mixing
3. Eliminate differences in composition	3. Separation of chemicals
	4. Phase separation
4. Eliminate differences in temperature, pressure, and phase	5. Change of temperature
	6. Change of pressure
	7. Change of phase
5. Integrate tasks; i.e., combine operations into unit processes.	8. Mixing and splitting of streams or batches.

In addition, Seider *et al.* (1999) show in Figure 2.2 how these parts are related to the entire design process and to each other, starting with process invention, synthesis and development of base case designs. Process design is rarely straightforward and it originates in the exploration of research, the availability of inexpensive raw material or the discovery of new markets.

Rather than discuss these steps in general, Seider *et al.* (1999) also discuss the concept of a synthesis tree (see Figure 2.2), which visually represents base case flowsheet development using the five synthesis steps. The synthesis tree suggests that flowsheet design is a sequential process. Realistically, there will be iteration between various tiers, particularly when process integration is carried out in both steps 2 and 5. The authors suggest that the synthesis tree is closely related to heuristic or rules of thumb typically used in design. Seider *et al.* (1999) describe them as they are applied to a particular process.

This methodology has limited applicability to dairy process design, due to its focus on chemical reactions, which are rarely carried out in dairy processing. If the first step is ignored, the methodology is reduced to matching chemical sources and sinks using industry-based heuristics. In this form, the method differs little from current dairy design practice.

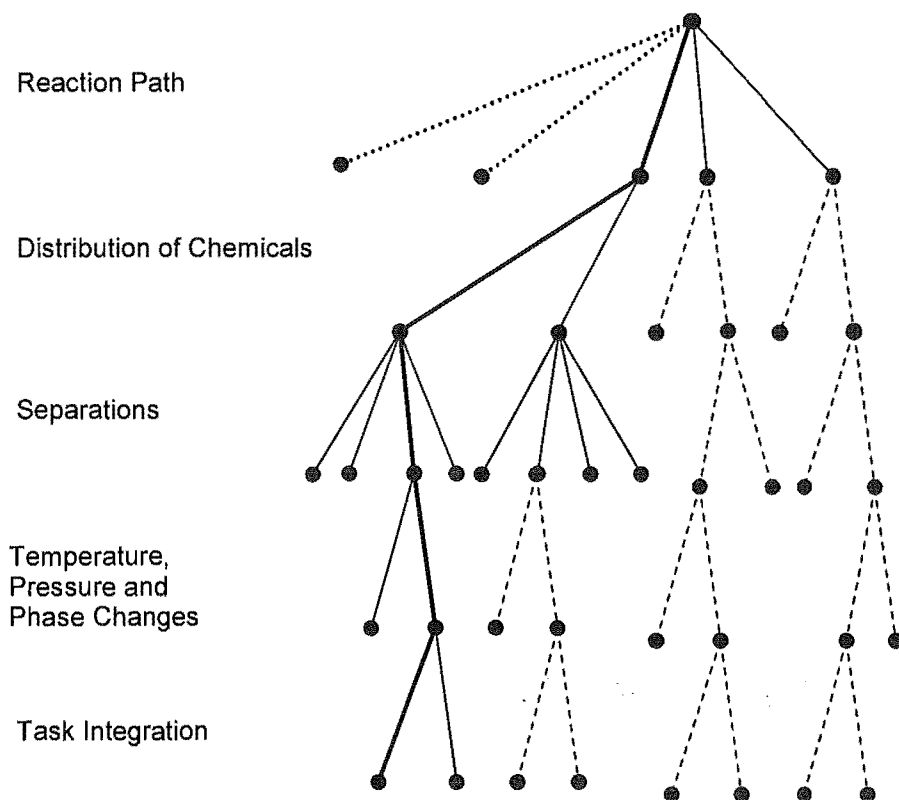


Figure 2-2 Inverted synthesis tree heuristics (Seider *et al.*, 1999).

2.1.4 Smith (1995) Methodology

According to Smith (1995), there are two approaches to designing a chemical process. The first approach follows the “onion logic”. In this logic, the designer starts by choosing the reactor if the process requires a reactor to transform the feed into a product. The designer then moves outwards by adding the separation and recycle systems. This is followed by the heat exchanger network and the utilities. The layers of the “onion diagram” shown in Figure 2-3 can represent this hierarchy symbolically. For

a process that does not require a reactor, the design will start with the separation systems followed by the heat exchanger network and utilities.

The decisions at each layer must be made based on the information available at each stage of the design. The equipment is added only if the addition can be justified economically. In this methodology, distillation is recommended as one of the most commonly used method for separating of homogeneous fluid mixtures in his process design approach.

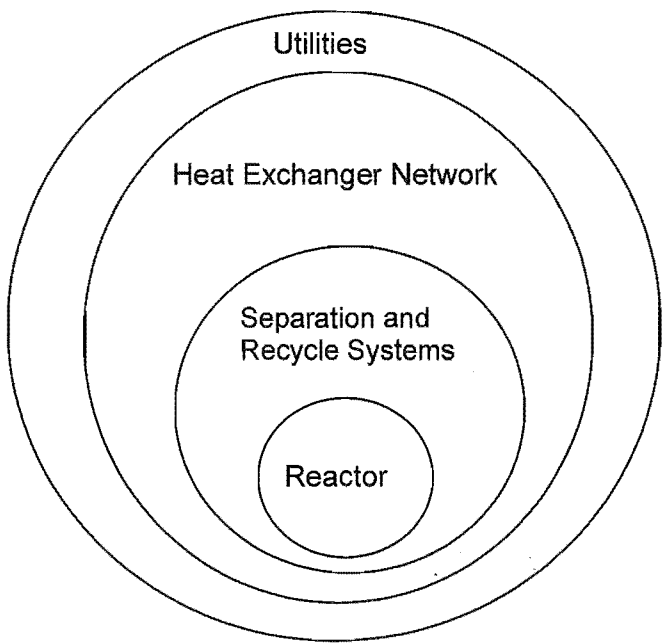


Figure 2-3 The “onion model” of process design Smith (1995).

Smith (1995) leaves safety, health and the environment to the final stages of design. Once a group of feasible flowsheets has been developed, he advocates reviewing the base case designs to optimise the heating and cooling duties for the heat exchanger network. Recovered heat can be used as an energy source for utilities within the plant, but where this is insufficient, external utilities are required. This part of the design problem can be clearly formulated mathematically and optimised subject to the constraints, cost and profits associated with each unit.

From the perspective of dairy process design, this methodology is more applicable than the methodology of Seider *et al.*, (1999), since the “onion logic” remains useful for systems with few chemical reactions. The emphasis on heat exchanger networks is also useful, since heat recovery is generally considered to be important in dairy processing. However, Smith (1995) does not address safety issues in an integrated manner within the methodology. Product safety is a critical consideration in all food processing industries, and the primary constraint on feasible flowsheet designs. Failure to include this requirement in the initial design stages will allow many unfeasible flowsheets to reach the screening stage (Figure 2-1).

2.2 Review of Methodologies for Conceptual Design

There are various methodologies for conceptual design available. Some methodologies are described as follow.

2.2.1 Douglas (1988) Methodology

Douglas described the conceptual design of chemical processes by considering the selection of petrochemical processes because they are the most common. He emphasised conceptual design because the equipment and structure used in the process flowsheet are fixed at this stage of the design activity. All other activities depend on the results of the conceptual design.

Douglas’s approach is heuristic, based on experience and understanding. He advocated that the procedure of chemical process design can be considered in a hierarchical context, where the process is broken down into a ranking of decisions at different levels. The design method he proposed follows a top-down approach strategy, with very simple solutions developed initially, followed by successive layers or levels of detail. This strategy starts with the design alternative at the highest abstraction level, and then structural refinements of the design are proposed at lower abstraction levels until a design is described by unit operations. During this process, the designs that have the highest expected profitability are refined first, and at every abstraction level, a numerical model is used to describe the design. Thus, the continuous parameters are quantified (Gavrila & Iedema, 1996).

Input information required for the conceptual process design is as follows (Douglas, 1988):

1. The reaction and reaction conditions
2. The desired production rate
3. The desired product purity, or information about the price versus purity
4. The raw materials and/or information about the price versus purity
5. Information of the rate of the reaction and the rate of catalyst deactivation
6. The processing constraints
7. Other plant and site data
8. Physical properties of all components
9. Information concerning the safety, toxicity, and the environmental impact of the materials involved in the process
10. Cost data for by-products, equipment and utilities.

The hierarchical systematic procedure that Douglas uses to develop a conceptual process design is described in three levels.

The first level focuses on the process flow diagram with the calculation of the characteristic sizes of each operation. This enables the costing analysis, e.g. the rate of evaporation for an evaporator. The second level is the detailed process design, normally shown as the piping and instrument diagram (P&ID), with associated mass and energy flows and the specifications for all equipment. The third level consists of the mechanical design to enable the physical construction of the equipment.

The hierarchical approach advocated by Douglas is relevant to dairy processing. It is particularly useful since it breaks down a complex design problem into manageable pieces. His methodology still allows heuristics to be used within the design process, although he focussed on the reactor/reactions in the same manner as Seider *et al.* (1999). Douglas' methodology has a disadvantage because his method is very rigorous, requiring substantial amounts of detailed information. Some of this data may not be available, or have a considerable amount of uncertainty. The other disadvantage is that the actual process for generating the candidate flowsheets is not discussed.

2.2.2 Shigley & Mischke (2001) Methodology

The design methodology of Shigley & Mischke (2001) takes a more holistic approach than other techniques. They claim that their design procedures enhances an understanding of the interaction between product and process through:

- A concept generation,
- A concept formulation,
- A concept comparison and evaluation,
- A concept selection.

A design is always subject to certain constraints. Shigley & Mischke have described the phases of design, beginning with recognising the need and making the decision to do something about it. After many interactions, the process ends with the presentation of the plan which will satisfy the need.

They argue that the first stage of design is to establish the need. According to Shigley & Mischke there is a clear difference between the statement of the need and the identification of the problem. They argue that a need is a requirement for opportunity that usually goes unnoticed, until highlighted by somebody or some event. The difference is that the need is often not apparent until a problem occurs, at which time it may be much easier to recognise. The recognition of the problem is usually triggered by a particular adverse circumstance. A process design may be developed in response to either a need, such as customer request, or a problem such as, the inability to meet current processing requirements for capacity, quality, functionality or pollution.

It is important to identify the problem along with all relevant constraints and objectives. Some constraints and requirements are easily quantifiable, such as:

- The processing capacity,
- The product specifications or characteristics,
- The project budget.

However, some other requirements or constraints are more qualitative and difficult to define explicitly in the design process. Qualitative requirements or constraints can include:

- Good controllability and operating flexibility,
- Minimal environmental impact and risk,
- A safe environment for workers,
- A design with good flexibility for new product types and future expansion.

There are two options for process design. The first option is to build on the existing design. This approach provides the designer with a low risk starting point and a good chance of identifying a feasible design solution. However, this approach can also produce sub-optimal designs because it is based on the older superseded technology. The second option is to start completely from scratch and use several alternatives as the starting points. Either way, it is important to identify the starting point.

Identify the Space of Design Alternatives

Candidate flowsheets are identified by establishing the properties and specific characteristics of the raw material along with an assessment of the constraints on the design, process, products, and environment. There are multiple iterations or feed back loops between the phases of the design, the complete process from start to finish is often outlined as shown in Figure 2-4. These loops may have to be traversed many times until the concept is generated and the recognition of the need is defined.

This approach is very useful in order to obtain the best results, to increase efficiency, and to make best use of the integration opportunities at each step of the conceptual design. Proceeding in this manner, there is an advantage of being able to assess the operability of a design because a review of the results at each step can be undertaken.

The methodology for conceptual design does not inhibit creativity during the process of selection of concepts. Shigley and Mischke (2001) argue that the many feed back loops in their methodology stimulates the emergence of new concepts and encourages the integration opportunities at each step of the conceptual design. These phases are unlikely to have emerged by any other means.

Dairy processing still allows heuristics to be used within the design process; heuristics do not focus on the reactor/reactions in the same manner as the design methodology of Seider *et al.* (1999). A disadvantage of this method is that it is very iterative, and may

be time consuming for a complex design. Another disadvantage is that the actual process for generating the candidate flowsheets is not discussed.

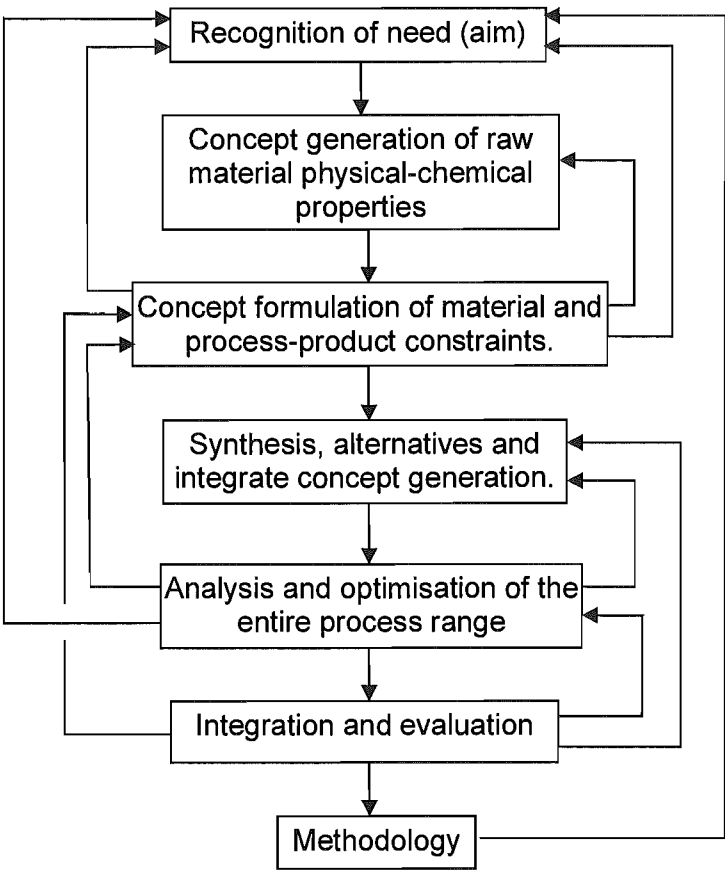


Figure 2-4 The phases of design of processes arranged from Shigley & Mischke (2001).

2.3 Design Management

The design processes in chemical engineering are difficult to support, particularly the conceptual designs with respect to tool support in a collaborative design process. Design management supports the coordination in the dynamics of the design process. As it is often the case, success depends on a good management as well as a good technology (Linnhoff, 1994).

Design management is the method to organise the design process better, and it is gaining popularity within the design community (Baya & Leifer, 1996). Using design

management as a tool provides an understanding of the information handling behaviour and helps to facilitate the design process. Design management is also a good tool to build and support information driven processes. Information management in conceptual design is the process of capturing and organising design information in such a manner that it can be retrieved and reused later (Baya & Leifer, 1996).

The design process is highly creative and many design alternatives are explored with both unexpected and planned feedback occurring frequently. Therefore, it is inherently difficult to manage the design processes (Nagl *et al.*, 2003). The design management of multidisciplinary teams provides precise communication, effective use of available design tools, appropriate application of materials, respect to the legacy of previous designers to meet user expectations and the environmental constraints (Hales, 2000).

The management system covers products, activities and resources, and their mutual relationships (Nagl *et al.*, 2003), in which many fundamental design alternatives are explored and analysed.

2.3.1 The Management of Design Process

Hales (2000) considers the management of the design process as more than just carrying out the obvious process design. He defines engineering design as the process of converting the idea or the market need into the detailed information from which a product or technical system can be produced. Despite the great advantages in technology, computational tools, information transmission and human factors, many designs still do not live up to user expectations or they fail in service for a variety of reasons. A systematic analysis of the design process usually reveals the causes of the failure.

Ten critical factors described by Hales are ones observed to have been the primary contributors to failure in design. They are listed as follows.

1. Defining a problem
2. A working design team
3. The right tools for the job
4. Communicating effectively
5. Getting the concept right

6. Keeping it simple
7. Making the function clear
8. Tackling safety
9. Selecting materials and parts
10. Details in the design.

Westerberg *et al.* (1997) also proposes specific approaches that are centred on the management of the available and derived information for the study and support of design processes. They were researching how to carry out studies more effectively and jointly with the industrial partners, and how to identify the features they needed for managing the information to study and improve the design processes. In the course of their study, they made general observations on the effect of different individual behaviour patterns within the design group and related this to the success of the design process operations.

3 General Aspects of Dairy Process Design

3.1 Dairy Process Design

There are several significant differences between petrochemical and dairy processing. These differences have considerable impact on the overall constraints, the objectives of a design brief and subsequently the conceptual design process. The main differences are described in the following sections, along with their design implications.

In the dairy process design, the initial information required is as follows:

1. Information concerning the raw material composition, safety, toxicity and environmental impact of the material involved in the process
2. Volume of the raw material to be processed
3. Physical properties of all raw material components
4. The desired final products and production rate
5. Desired product purity or information about the price versus product specification
6. The processing and product constraints
7. The waste that may cause environmental damage.

Comparison between petrochemical and dairy processes is shown in Table 3-1.

Table 3-1 Comparison between the petrochemical and dairy industry process approach.

Petrochemical approach	Dairy approach
Impurities can be removed later.	Pathogenic organisms have to be removed initially (e.g., by pasteurisation).
Life time of the plant or of the resources are limited by the sources.	The life time of the plant keeps growing with increased raw material production.
Streams can be recycled any number of times.	Recycling is limited by many constraints. Recycling can increase physical or thermal damage to the product. Recycling must be avoided to prevent microbial growth.
The components do not suffer major damage while being handled.	The raw material must be handled carefully to conserve the components' properties.
Processes can run continuously.	Some dairy industry processes must be batch. Most will be semi-continuous.
Long lasting shelf life products.	Short shelf life products.
Reaction time is important.	Heat treatment holding time is important because some components are heat sensitive.
Process are designed to operate at a constant throughput for long periods.	There are large seasonal changes in milk supply volumes throughput during the season.
Corrosion is an area of great concern, particularly atmospheric corrosion.	Fouling is a daily concern.
Some of the products are used directly, or indirectly as intermediate products by the customer. Low grade products can still be sold.	Consumer food safety is critical. Unhygienic products are unacceptable.
Continuous process with limited flexibility in process design.	Need flexibility to produce products of many different specifications.
Feed supply can be stopped.	Feed supply from the cows cannot be stopped and all must be processed.

3.2 The Perspective of Methodologies for Design Dairy Processes

Although there are many general design methods available, there is little or no evidence of the availability of a methodology of design in the dairy industry.

A wide range of process synthesis techniques have been described in the literature. The two most common approaches are based either upon heuristics (Douglas, 1988) or the optimisation procedures that extract the best design from a superstructure (Fraga & McKinnon, 1994; Grossman & Kravanja, 1995; Jaksland & Gani, 1996 and Steffens *et al.*, 2000a).

3.3 Process Definitions

Many dairy design processes in the form of block diagrams exist in the literature (Kessler, 1981; Robinson & Tamine, 1986; Bylund, 1995; Chandan 1997; and Walstra *et al.*, 1999). They define the procedure in order to obtain a defined final product.

The process of design involves the modelling of objectives, options and choices after analysis of the main objectives and constraints in each level of design.

The following items will be defined.

- a) The feed
- b) The process
- c) The product
- d) The side product
 - Co-products and by-products
 - Waste products and emissions
- e) Throughput
- f) The objective of the process
 - Principle objective
 - Other objectives (process and product)
- g) Constraints
 - On the product

- On the process
- h) Co-requisites

a) The Feed

A feed is defined for each process. The overall feed will always be raw milk (generally from cows) that can vary in composition and with a daily feed volume that varies during the season. Case studies will be presented in Chapter 7 with volumes varying from ten litres to two millions litres per day (one cow to 100,000 cows approximately).

b) The Process

Processes are normally defined here as a single operation within the plant, e.g. evaporation of whole milk to produce concentrated whole milk. However, when operations are integrated, a process might include many unit operations, e.g., production of whole milk powder from raw milk which includes pasteurisation, evaporation, drying and other processes. Processes may have a range of scales. A typical process representation is shown in Figure 3-1. Where A and B are the feed streams, A^+ and B^- are the enriched and depleted streams respectively. B^+ may be a co-product or by-product stream and S is a waste stream.

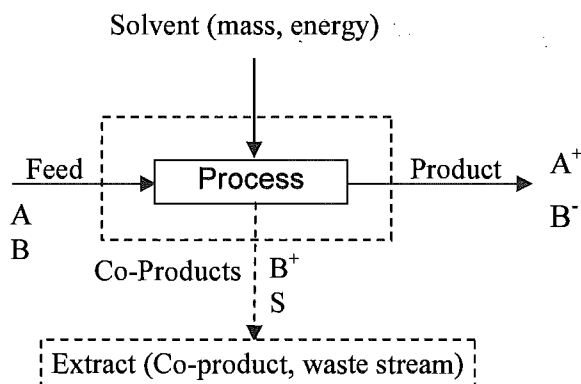


Figure 3-1 General process model and main parameters.

c) The Product

A product is the desired principal output from a process, e.g., milk powder is the product of a spray drying process.

d) The side product

A side product is a flow coming out of a linear flowsheet, after producing the main product. It may be co-products and/or by-products, waste products or emissions.

- **Co-Product**

A co-product is something regarded as a valuable product in its own right, that can be sold to customers or processed further. A co-product is the result of the difference between feed and product, sometimes referred to as “left over” during this design.

There can be more than one co-product. They are the alternative products produced as a result of the product’s manufacture, which can sometimes be produced as a necessary step in obtaining the product, or simultaneously with the product, or perhaps as a process further downstream.

- **By-product**

By-product is something of little value, no value or negative value. When it is not saleable, it may be used to offset disposal costs. If the by-product has a value, it can become a co-product. For example, in the past whey was a by-product from cheese making as it was disposed of, but now it is processed and sold as a co-product.

- **Waste products and emissions**

A waste product is a material left after the product, co-products and by-product have been taken out. They can be the result of the clean in place (CIP) process.

Emissions include hot air and noise.

e) Throughput

The amount of material passing through a system from input to output (especially of a raw material) over a period of time.

f) The objective of the process

The objective is normally to make a product from a given feed stream with specified throughput, and generally with minimum cost.

There are often related objectives of a process.

If casein is made, for example, the fat and the whey must also be processed. A processing site may include plants for the production of casein, butter, whey protein concentrate, lactose and milk minerals. With the integration of components in the dairy processes, virtually every component of milk will be used in an integrated dairy process design as shown in the following sections.

The casein process, for example, has two objectives as follows:

- *The principle objective* is to make dry casein from skim milk.
- *The other objectives (process and product)* are to be able to process fat, whey, lactose, and perhaps milk minerals.

g) Constraints

- *On the product.* The product will be required to meet some specifications.
- *On the process.* An example of this type of constraints on the process is that temperature must be less than 70 °C to avoid denaturation.

h) Co-requisites

They are often utilities which must be available on the processing site to enable to process the function.

3.4 Art, Science, Technology, Engineering and Process Design in the Dairy Industry

The distinction between art, science, engineering process design and other aspects of design and technology is important in this context of design.

Art

The overall activity of dairy design might be considered to be an art. The creative application of fundamental needs or ideas is used in the development of a design. Dairy process design is the combination of science, technology and engineering in a creative way that helps to make process design challenging and fascinating to a chemical engineer.

Science

An active research capability exists in scientific areas such as microbiology, dairy chemistry and product development in the dairy industry.

Science is primarily concerned with the scientific principles underlying the intended process (Scott *et al.*, 1992).

Technology

Process equipment is defined as a technology if it is not designed only from a fundamental calculation, but is based on experience or developed by empiricism. Examples are butter making churns, centrifugal separators, decanters, clarifiers and leak-proof valves.

The majority of process technology used in the dairy industry is “off-the-shelf” and supplied by a small number of international equipment suppliers. The industry has little input to the process design and development for most of these technologies (Nicol *et al.*, 2001).

Engineering

The link between the chemical engineering and dairy process industry is a rewarding field for the exercise of chemical process engineering. This is because the dairy industry uses most of the unit operations found in the chemical engineering discipline, for example, mass and energy balance, heat transfer, fluid flow, evaporation and drying just to mention a few. There are many challenges including the ever-present need for hygiene, the need to minimise fat globule damage and the pressure of handling the perishable raw material that keeps on coming regardless of the plant readiness.

Mechanical engineering design will include aspects related to the strength of the equipment and the manner in which it is constructed. Process design impacts on this when there are special requirements such as hygienic design or corrosion resistance of the material of construction (Jackson, 1985; Garverick, 1994).

Process Design

In the context of the dairy processing industry, a process design is essentially a collection and sequencing of equipment and methods to transform a defined flow of feed material into a specified product. The process design has a specified feed material, product, operations and throughput.

Mechanical and process design will overlap to a small extent for such matters as hygienic design and selection of materials for corrosion resistance and cleanability (Vickers, 1979; Fryer, 2001).

3.5 Raw Material Supply and Characteristics

The raw material, milk, has some special features that distinguish it from other feed materials. Milk is subject to natural variations:

a) Varying supply quantity per day and per season

There is a considerable variation in the milk supply volume through the dairying season (Walstra & Jenness, 1984). Since the incoming volumes cannot be controlled, a seasonal incoming volume must be estimated. Economies of scale must be considered in the context of any changes in milk volumes, and processes must be able to cope with the peak milk flow (Bloore, 2001).

During the months of lactation, the cows are milked at least once and normally twice per day. If they are not milked, not only do they not accumulate milk, they may lose the ability to produce it. In this respect, the dairy industry is similar to other sections of the food industry in which many foods must be harvested when ready and cannot be kept.

b) Variable composition

The composition of milk for processing varies through the dairying season, particularly for pasture fed animals. Important aspects of the raw material composition must be considered in design. The composition of milk changes during the season, e.g., fat and protein. However, the composition of milk has typical ranges. There may be subtle differences in the structural elements and physical properties between different lots of milk as a result of natural variation or changes occurring after the milking. This natural

variation may have three causes. The first is genetic between cows or between individuals, the second is the physiological state, in particular the state of lactation, age of cow and gestation, and the third is environmental, particularly feed, climate and stress (Walstra & Jenness, 1984).

c) Heat sensitivity

Some components of the milk, especially the proteins, are heat sensitive. This limits the processing conditions because the protein denaturation occurs above 65 °C (Walstra & Jenness, 1984).

d) Shear sensitivity

The fat globule can be damaged easily by mechanical treatments, pumping and transporting (Bylund, 1995).

It has been found also that processing conditions like agitation and turbulence might cause damage to the fat globule membranes, leading to hydrolysis of the fat and the slight impairment of the flavour (Kaylegian & Lindsay, 1995). The velocities in the process operations must be controlled to limit the shear forces.

e) Time-enzymic degeneration or degradation

Time is another important issue to consider, from the reception line to the final product process. To minimise enzymic degradation, which occurs when the raw and intermediate product is stored, the storage time and conditions must be taken into consideration during design. Short residence times are required when dairy products are stored warm.

f) Susceptibility to microbial growth

Microbial degradation makes milk a perishable material. Unlike petrochemical raw material and products, milk decays quickly when it leaves the udder and is exposed to oxygen, light and handling equipment. Therefore, sanitary and product safety requires regular microbial control and cleaning. Raw milk contains a number of natural bacteria, which will spoil it if it is not processed within about one day.

g) Functional Properties

The suitability of certain protein preparations like nutritional quality, flavour, solubility, gelling, swelling (water holding) and emulsification are dependent on composition, manufacturing and storage (Walstra & Jenness, 1984).

3.6 Product Safety and Fouling

The control of the microbial content of a product imposes strict constraints on processing. Milk processing needs to have:

- a. Traceability and product history that is available at any time
- b. Fixed processing requirements
- c. Heat treatment requirements, e.g., pasteurisation
- d. Minimal recycle or product hold-up.

Fouling and cleaning in design dairy processes. There is a serious fouling problem of milk within heat treatment equipment. The growth of fouling reduces the overall heat transfer coefficient. It also increases the surface area and roughness, which then creates sites for microbial growth. As a consequence the sterility of the process plant is lost and the product flow can also be restricted. Therefore, a periodic shut-down of the equipment for cleaning-in-place (CIP), which results in hours of lost production, is necessary.

Many studies have been carried out to quantify, control and reduce equipment fouling (Kastanas *et al.*, 1995). In virtually all types of heat transfer plants, fouling of heat transfer surfaces is the main cause of progressive decline in efficiency and performance with time. This phenomenon necessitates frequent cleaning of equipment and is of considerable importance in the dairy industry (Tissier & Lalande, 1986).

The need to clean equipment adds energy costs to the process. Fouling significantly affects the economics of the process, requiring capital expenditure on maintenance and CIP chemicals. In addition to downtime that increases the production cost, product safety sometimes requires stand-by equipment, used while CIP is taking place, in order to keep the process line going.

The most obvious problem with fouling is downtime. This is in clear contrast to petroleum plants, which can be run for years without cleaning. A typical dairy processing unit operation requires cleaning after every processing run of 8-12 hours and in the case of spray driers, every 5-6 weeks (see others in Table 3.2). As a result, frequent cleaning cycles are often necessary to remove deposits. More start-ups and shut-downs generally cause additional waste (Kohlbrand, 1998; Balannec *et al.*, 2002).

Table 3-2 Typical run times before cleaning (Howell, 1998).

Equipment	Run time before cleaning
Centrifuge	8-12 hrs
Pasteuriser	8-12 hrs
Evaporator	10-14 hrs
Spray Drier	5-6 weeks

Production scheduling is very important in dairy industry processing, since run time lengths are limited by fouling and microbial constraints. These constraints must be considered when developing process flowsheets.

3.7 Batch, Semi-continuous or Continuous Processing

With the current technology, the distinction between the batch and semi-continuous processes is quite clear, even though the exact definition of batch and continuous is not. For food processing, these can be defined as below:

- a) A batch process is normally defined by a volume or mass, in which the product is held in a fixed volume while it is processed (e.g., in a cheese vat) or accumulated during processing (e.g., in dead end filtration and silo storage).
- b) A continuous process is normally defined by a flow rate where there is a continuous feed into the process and a continuous flow of product out of the process.
- c) A semi-continuous process is a continuous process that is interrupted from time to time, perhaps for cleaning.

A continuous process can consist of a number of batch or semi-continuous processes. For example, a cheese plant is made semi-continuous by scheduling a number of batch cheese vats. Another good example is the spray drying of milk with a single drier fed by multiple evaporators, in which the drier may operate for up to a month continuously, but each evaporator runs semi-continuously for about 10 to 15 hours at a time (Bloore, 2001).

The batch or semi-continuous nature of food processing applies a constraint to energy integration. Start-up and shut-down of processes at different times requires that energy be stored or that alternative systems be put in place. Also batch or semi-continuous process adds storage requirements or scheduling needs to the process design.

Design of Batch versus Continuous Processes

Douglas (1988) developed a conceptual design for a continuous process first and then for a batch process in which it is necessary to make more decisions.

Decisions to be made for a continuous process:

1. Select the process units needed
2. Choose the interconnections among these units
3. Identify the process alternative that must be considered
4. List the dominant design variables
5. Estimate the optimum processing conditions
6. Determine the best process alternative

For a batch process, the following decisions must be made in addition to the above mentioned:

7. Which units in the flowsheet should be batch and which should be continuous
8. Whether all the processing steps should be carried out in a single vessel, or an individual vessel for each processing step
9. When it is advantageous to use the parallel batch units to improve the scheduling of the plant
10. The location and size of intermediate storage that is required.

Malone *et al.* (1985) suggests that the best approach to design a batch process is to design a continuous process first. They show that the choice between batch and continuous processes depends normally on the size of the process design, because the batch process alternative would be the first step to take for a small size process. According to the approach of the Douglas (1988) methodology, it is simpler to screen the process alternatives and to determine the best process flowsheet.

This strong bias towards continuous processing seen in the chemical industry does not always suit dairy processes, e.g., in cheese making.

3.8 Other Significant Aspects for Conceptual Dairy Design

In conceptual dairy design, there are other aspects that remain to be considered. The determinations of these significant aspects are briefly described below.

3.8.1 Environmental Factors in Dairy Process Design

Environmental concerns in the selection of the process design, as well as the unit operations, are important in dairy process design. An example, of this is the wastewater from dairy plant processes, which normally contains fat, milk proteins, lactose, some lactic acid, minerals, detergents, and sanitisers. Normally, a major fraction of the pollutants is in a dissolved organic and inorganic form. The wastewater strength and quality varies even within plants producing the same products (Jones, 1974). The determination of the significant sources of dairy food plant waste requires an understanding of processing of dairy products and the unit operation involved in order to evaluate the pollution potential.

3.8.2 Site Location and Limitation

The proximity of the raw material supply, and the product consumers, will have an impact on the site location, and will reflect the additional transportation cost (Bachmann, 1981).

The site location often has a significant impact on the selection of waste water treatment facilities. Sites in urban, coastal and rural areas may have very different waste water solutions. In the urban location they may be restricted by odour, noise or perhaps

aesthetic regulations. The availability of utilities, e.g., water and electricity, will depend also on the geographical location.

3.8.3 The Management of Design Process in the Dairy Industry

Hales (2000) stated ten critical factors in the design process (see Section 2.3.1). These ten critical factors for the managements of the design process are adapted to the dairy process industry.

Critical Factor 1: Define the objective and the outcomes

The aim of the dairy industry is to make profits for the shareholders (farmers). One looks for the outcomes, with no unnecessary constraints. In general, the real design problem is never clearly defined, or the wrong problem is identified. For example, the farmer needs to make a profit from her or his land that will provide a living; there may be product choices other than milk.

Once the outcomes have been defined, the criteria for selecting an appropriate concept must be established in the form of a design specification. Here, all the requirements to be met by any solution are listed. If the requirements are inaccurate or incomplete then the design process will be flawed from the start with the introduction of fictitious constraints. This can result in the concept selected being over constrained and therefore it will not be an optimum solution to the objective. Deficient design specifications also result in a huge waste of effort, money, materials and time.

Critical factor 2: Select the most appropriate Dairy Design Team

Dairy design teams generally consist of mechanical, electrical, civil, chemical engineers (with economics skills), marketing personnel, microbiologists, chemists and food technologists. Each of them has their functional role in the design team based on their particular technical expertise and experience.

Critical factor 3: The right tools for the job.

There are a variety of chemical process design methods or approaches discussed in the literature. There are also a number of different process design software packages available commercially. The most appropriate technique or tool will depend on the nature of the design project.

Care must be taken to focus on the result required. Crosschecks are essential to make sure that the right approach is taken. Since not all the methods and techniques available for chemical process design are suitable for dairy processes design; one needs to analyse and synthesise which tools should be used and why, when and how in respect to the design project objective.

Critical factor 4: Communicate effectively

Effective communication is as important as the idea during the process design. For example, a deficient design specification, coupled with inadequate communication of design from the manufacturer may lead to an unacceptable performance of the machine and thus inability to fulfil the final product specification required by the customer.

Critical factor 5: Getting the concepts right

Once the objective of milk product has been defined, it is possible to start generating ideas. This leads to the specific key concepts like the products and process constraints, utilities, and equipment flexibility.

Hales (2000) described the difference between the invention and intellectual property terms. An invention is not necessarily a design. This is because there is a fundamental difference between an inventor having an inspiration on Thursday and a design engineer producing an acceptable design concept within time, budget and specification constraints by Thursday.

Critical factor 6: Keep the design simple.

It is important to look for simpler ways of doing the same job in the dairy process. Complex geometries should be avoided because they are bug traps. Equipment that can not be easy disassembled should be avoided if possible because it will require cleaning and perhaps be subject to fouling although, there are many new technologies of compact and self-cleaning automated equipment.

The design concepts must be developed progressively into a practical, reliable and safe result. A simple design should be developed first with the successive layers of detail to be added as necessary. Then one looks for ways of stripping away layers of detail until the simplest way of achieving the goal is found.

The process insights are the simple representations that allow engineers to discover better design options. Researchers on short-term memory studies demonstrated that humans can deal with about seven to eight chunks of information at any one time. Really outstanding people might make it to nine. Humans cannot be asked to be innovative in a space with too many concepts whirling about at the same time (Westerberg *et al.*, 1997).

There are specific guidelines available for these phases of the design process. These guidelines describe factors of particular importance, the first of which is simplicity. The design should be made as simple as possible by, for example, choosing the number of milk components to the most important ones. Milk has more than 100,000 different molecular species but most of these have not been identified. The principal components are those present in the largest concentration (Walstra & Jenness 1984). Most of the minor constituents are vitamins, metal ions, and flavour compounds (Fox & McSweeney, 1998).

Critical Factor 7: Making the functions clear

The clarity in the dairy design requires making sure that the design itself explains how the things are to be put together, and the function of each operation. This applies for example, to the function of all cleaning chemicals in the clean-in-place (CIP) room.

The particular issues in the dairy industry need to be made clear since the lack of clarity in dairy design creates ambiguities and design weaknesses. These may not be immediately obvious because there can be a tendency to use from the conventional arrangements instead of the unconventional design.

The design steps need to have a clear function e.g., a dairy evaporator only removes water but not milk other components.

Critical factor 8: Safety

Safety, for equipment and personal health is an important part of the dairy process design. For example, a leak in the regeneration section of the pasteurisation process might not be found immediately so the section must be designed to have a pressure differential preventing contamination of pasteurised milk.

Critical Factor 9: Selecting equipment and parts for the process design

A critical factor in the embodiment of the dairy process design is the selection of equipment and standard parts which can be purchased off the shelf. Some equipment parts will be standard but many need to be designed individually.

Critical Factor 10: Details in design cannot be ignored: Top-down approach

The design concepts and analysis must be kept simple. Start with the broad concepts and then work out the detail. Consideration of the constraints in all alternatives will reveal the essential details in the conceptual design and thus balance a good design concept.

These ten critical factors are adapted to the dairy process industry, as shown in Figure 3.2.

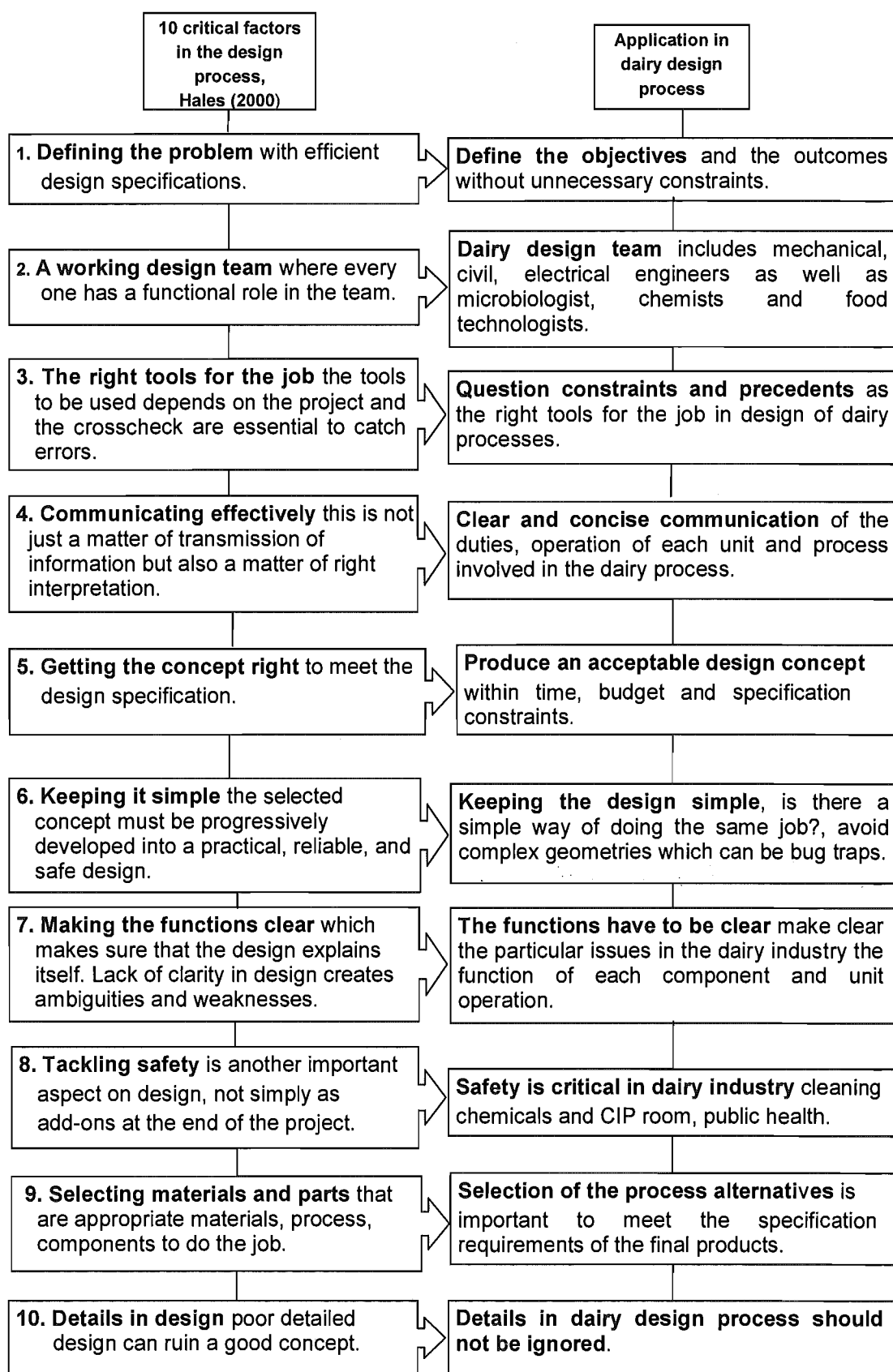


Figure 3-2 Application of critical factors proposed by Hales (2000) in the design management for dairy industry, with new concepts added by the author.

3.9 Summary

Several conceptual design methodologies were described in Chapter 2, most of which were developed in petrochemical industries. The dairy process industry differs from the petrochemical process industry in several ways. There is variation in volume and composition of bulk milk arriving at any factory due to seasonal variation, collection area, genetic variation between breeds and individual animals, physiological (age of the cow and stage of lactation), and environment (feed, climate and stress). As a result of these factors, the main components such as protein, fat and lactose vary within typical ranges. Despite the variations in composition there is a need to have consistent final products that meet the consumers' needs and specifications. The food industry is constrained by the need to clean. Also, some processes, by their nature, are batch and most will be semi-continuous. For these reasons and more, some of the petrochemical methodologies are not entirely consistent with the specific requirements and objectives of dairy process design. These differences have considerable impact on the overall constraints and objectives of the conceptual design process.

The relevant design issues for the dairy process industry, however, are still expressed in the conceptual design framework of Douglas (1988). Focussing on the reactor as a first stage is not particularly relevant, but dairy processes may have other operations rather than reactors, which can be used as a starting point. Although the dairy industry differs from petrochemicals in some significant ways, there are several aspects of the conceptual methodologies which are relevant and useful for developing a conceptual design methodology for the dairy process industry. These methods will be used as a basis for developing a specified dairy design methodology in subsequent chapters.

4 Unit Operations in the Dairy Industry from a Process Point of View

Dairy processing is dominated by the separation and heat transfer processes. Unlike petrochemical processes, there are only a few reaction operations in dairy processing. Dairy process design is strongly influenced by certain requirements such as food safety, minimising protein denaturation by using temperatures less than about 70 °C and minimising mechanical damage of the fat globules. Consequently, the final flow sheet is dominated by unit operations that can achieve these requirements.

Designs based on existing operations are likely to engender the greatest confidence. In order to develop a design, the engineer must have a sound fundamental understanding of existing processes and of the limits and constraints imposed by physical and chemical properties of the materials processed. A systematic comparison of those physical and chemical properties will then reveal where existing operations may be improved (Scott *et al.*, 1992).

The process point of view based on the unit operations described in this chapter aims to define aspects inherently related to the conceptual dairy process design by defining different types of constraints in the unit operations, as below:

1. Process constraints
e.g., maximum viscosity to achieve film flow in evaporators
2. Design constraints
e.g., maximum hygienic pump size available
3. Product constraints on the process
e.g., maximum heat treatment for proteins
4. Product constraints on the process operation
e.g., maximum operating time with minimal bacterial growth
5. Other constraints
e.g., maximum environmental emissions

The product constraints will be discussed in Chapter 5, while constraints relating to particular unit operations will be discussed in this chapter.

Unit operations are divided into seven main categories for discussion in this chapter:

1. Heat transfer
2. Separation
3. Mixing and/or blending
4. Reaction
5. Storage
6. Packaging
7. Other emerging processes that may be suitable for dairy industry

For pathogen control:

- a. High pressure
- b. Ultraviolet (UV)
- c. Electromagnetic waves
- d. Electron and gamma rays

4.1 Heat Transfer Operations

4.1.1 Overview

Heat transfer operations are widely used in most chemical process industries and are an essential part of the manufacture of dairy products. There are four main uses of heat transfer in the dairy industry:

1. Heating to destroy pathogens i.e., pasteurisation, thermisation and sterilisation
2. Cooling to prevent bacterial growth
3. Heating or cooling to bring a product to a required processing temperature
4. Heating for separations such as evaporation and drying (see Sections 4.2.3 and 4.2.4).

In the dairy industry, heat transfer takes place in the form of convection, conduction and radiation, though the first two are the most common (Bylund, 1995).

General issues of all heat treatments

There are constraints in the process, products and design. An excessive temperature and time (above 80 °C for longer than about 15 seconds for milk) will cause protein damage or denaturation that can affect product functionality. High temperatures also cause fouling on heat transfer surfaces, which reduces heat transfer rates and may allow bacterial growth. All surfaces wetted with milk must be cleaned at least once every day. A consequence of this is cleaning waste that is produced from the rinsing, caustic wash and acid wash during the cleaning-in-place (CIP). These cleaning waste effluents increase costs through chemical costs, product loss and treatment costs.

The energy costs associated with heating and cooling are very significant and every effort must be made to recover heat or cold wherever possible. A classic application is in pasteurisation, where energy usage can be reduced if the heated milk exchanges heat with the cold milk to preheat it (Kessler, 1981).

The consequences of cleaning waste and energy costs are typical of many operations in that they demonstrate that unit operations cannot be viewed in isolation. Furthermore, the consequences of cleaning system and energy design choices should be recognised early in the design process.

There is a variety of choices for the type of heat transfer used. From a design perspective, the first distinction made can be between direct and indirect heat transfer. Direct heat transfer involves directly mixing a heating or cooling fluid (e.g., steam, hot water, or cold water) with the product, while indirect heat transfer involves transferring heat from one fluid through a barrier to the other fluid.

4.1.2 Direct Heating and Cooling

The product is heated or cooled by direct contact with the heating or cooling medium. The advantage of this is that the product is brought to the new temperature over a very short period of time, which for heat sensitive products such as milk may cause less damage. Further, no heat transfer surfaces are required for direct heat transfer, so much

less fouling occurs. For all direct heating or cooling of product, potable liquids or vapours will be required.

Direct heat transfer can occur between a variety of different phases in different configurations:

1. Injection of steam into liquid (direct steam injection)
2. Passing liquid through a steam or vapour chamber (steam infusion or direct contact preheating)
3. Injection of hot liquid into a low pressure chamber (flash cooling)
4. Mixing of solid product with hot or cold water (e.g., during casein washing, see Section 5.6.1).

Drying can also be considered as a form of direct contact heat transfer and this is discussed in Section 4.2.4.

The process of milk sterilisation can use steam infusion or direct steam injection followed by flash cooling. In steam infusion, milk droplets fall into a chamber of high-pressure steam and the period of the fall matches the desired holding time to achieve sterilisation.

For direct steam injection, steam is injected into a pipe through which the products flow and causes rapid heating of about 140 °C and 10% to 15% dilution (Grandison & Lewis 1996; Lewis, 1986a). The product is then held, by flowing through a tube, for 2 to 4 seconds to achieve sterilisation. The product can then be passed into a low-pressure flash vessel, immediately dropping the temperature below 80 °C and controlling the heat treatment to the minimum required. This causes some of the water to evaporate and pass out as vapour. As a result, the solids content of the product is restored to its original value. Flash cooling will also remove both desirable and undesirable flavour components and dissolved gases.

Direct steam injection is often used to heat water, as the capital cost is much less than that of a heat exchanger and the energy cost is the same. However, the overall cost and inefficiency of supplying steam may be more than other processes that produce hot water directly. If a substantial amount of hot water is required, a dedicated hot water “boiler” may be a better option than a steam boiler and direct steam injection.

Direct heating and cooling with hot and warm water is effectively used in casein washing where the requirements for both wash water and product temperature changes are met coincidentally. Some cheeses, such as Gouda cheese and Cheshire cheese, involve a step of direct addition of hot water that is used to wash the curd and to change its temperature. In some processes, Mozzarella cheese is directly heated in a brine bath. Most brine salted cheeses, e.g., Gouda, are cooled rapidly by immersion in brine, helping to control the types of bacteria that will grow.

Other forms of direct cooling by the addition of ice or liquid gases could give rapid cooling but are currently unknown in the industry.

4.1.3 Indirect Heating and Cooling

In the dairy industry, indirect heating and cooling are more common than direct heating and cooling. The heating or cooling medium and the product are not in direct contact, but separated by a conducting barrier (normally stainless steel). Heat is transferred from the medium through the contact surfaces into the product in a variety of ways (Spalding, 1992).

Several types of heat exchangers are available, i.e., plate, tubular (shell and tube, shell and coil, double tube, triple tube) and scraped surface (Kessler, 1981). In addition, a heating or cooling jacket is often used to heat or cool a vessel.

Heat exchangers used for dairy products must be able to be cleaned and inspected easily to ensure that surface fouling is removed. This is possible with some shell and tube designs but this requirement normally leads to the use of plate heat exchangers or tube-in-tube exchangers. Shell and tube heat exchangers can be used for water heating or

vapour condensing where there is no risk of bacterial growth leading to food contamination.

High viscosity materials often require scraped surface heat exchangers in which the surface is scraped to ensure mixing of heated or cooled product and to minimise fouling. These can be used for heating concentrated milk or for cooling viscous products such as butter and ice-cream.

General indirect heat transfer examples (Kessler, 1981) include:

- Milk cooling after milking on farms by bulk tank coolers or by immersion cooler units
- Milk pasteurisation
- Preheating of the milk feed to evaporators
- Heating of the air stream to drier chambers
- Temperature control of jacketed cheese vats
- Chilling of pasteurised milk and intermediate products before storage in silos in order to control microbial growth
- Feed preheating for centrifugal separators.

Heating media used includes hot product, hot water, steam, hot oil (for air heating) and hot combustion gases. Cooling media includes liquid refrigerant, cold product, cold water, chilled water, alcohol brine and glycol solution.

Design Information and Constraints

Heat transfer coefficients for these heat exchangers can be estimated from values found in textbooks or manufacturers' literature (Walas, 1990; Holman, 1992; Mills 1999), though for plate heat exchangers the equations are not always openly available so the designer must rely on supply companies. Typically, the temperature approach (the temperature difference between the hot stream in and the heated stream out) is in the range 3 °C to 8 °C for plate heat exchangers and at about 20 °C for air heaters.

The size of the heat exchanger is specified by the product flowrate and the required rate of heat transfer. Equation 4-1 is a general formula used to calculate the required heat transfer area:

$$A = \frac{\dot{m} C_p (T_{\text{out}} - T_{\text{in}})}{U \Delta T} \quad (4-1)$$

where U is the overall heat transfer coefficient, A the surface area over which heat transfer can occur and ΔT is a suitable temperature difference between the two fluids, T_{in} = stream inlet temperature [K], T_{out} = stream outlet temperature [K], \dot{m} = mass flow rate [kg/s] respectively. Typical overall heat transfer coefficient (U) for the plate heat exchanger is $4000 \text{ W/m}^2 \text{ K}$.

For the unbalanced co-current or counter-current exchanger, the most commonly used mean temperature is the logarithmic mean temperature difference ΔT_{LM} (Thomas, 2000; Walas, 1990; Sinnott, 2000). The logarithmic mean temperature derivation can be found in texts (Holman, 1992).

There are four major constraints on the design. These constraints are described here as follows:

1. Process Constraints.

The product must be in liquid form but slurries can also be heated or cooled if the particle size is sufficiently smaller than the gap in the heat exchanger. High viscosity liquids can be processed if they do not violate pressure constraints (below).

2. Design Constraints.

Very large plate heat exchangers can be constructed but the gaskets used limit the maximum operating pressure of any exchanger. Thus, the pressure drop is directly limited and the flowrate is indirectly limited. The maximum pressure at which they can operate is 25 bar gauge, but they normally operate at below 15 bar gauge (Thomas, 2000). Further, the flowrate is limited to approximately 200,000 L/hr by the maximum

size of hygienic pump available. The maximum operating temperature is limited to about 250 °C (Sinnott, 2000) due to the performance of the available gaskets materials.

Sanitary design requires that materials for the heat exchangers are mostly stainless steel.

3. Product Constraints on the Process Design.

Excessive temperatures above 80 °C for longer than about 15 seconds damage the protein. Similarly, excessive shear forces may damage the fat globules, causing impairment of the flavour as the fat becomes susceptible to oxidation or lipolysis (Bylund, 1995).

4. Product Constraints on the Process Operation.

One of the problems is fouling, which can restrict the operating time to about eight hours.

4.1.4 Heat Treatment for Pathogen Control

Pasteurisation, sterilisation and thermisation are the heat treatments for pathogen control operations of milk processing. Pasteurisation destroys pathogenic organisms typically by heating milk to 72 °C and holding it for 15 seconds before cooling. Thermisation uses a lower temperature of about 65 °C to extend the keeping time of unpasteurised milk and is sometimes used before making some hard cheeses. Sterilisation is designed to destroy all micro-organisms and spores, and to inactivate enzymes (Hinrichs & Kessler, 1995). All the processes aim to retain as many as possible of the food organoleptic and nutritive properties of the raw material.

Table 4.1 shows a summary of the combination of temperature and typical holding time in the heat transfer for pathogenic control in the dairy industry.

Table 4-1 Heat transfer for pathogenic control (Bylund, 1995).

Process		Temperature	Holding time
Thermisation		63 – 65 °C	15 - 30 seconds
Pasteurisation	(LTLT)	63 °C	30 minutes
Pasteurisation	(HTST)	72 – 75 °C	15 - 20 seconds
Pasteurisation of cream etc.	(HTST)	> 80 °C	1 - 5 seconds
Ultra pasteurisation		125 – 138 °C	2 - 4 seconds
UHT (flow sterilisation)		135 – 140 °C	a few seconds
Sterilisation in container		115 – 120 °C	20-30 minutes

LTLT = Low temperature long time.

HTST = High temperature short time.

UHT = Ultra high temperature.

Thermisation

This heat treatment process is used to extend the storage time of milk by applying a moderate heat treatment to raw milk at 63 °C to 65 °C with an effective holding time of a minimum of 15 seconds and maximum of 30 seconds, followed by cooling. The purpose of this thermal treatment is to extend the storage time of cooled milk and for treatment of milk before making some cheeses. When a short storage period cannot always be maintained, thermisation can reduce loss of quality (Spreer, 1998).

The treatment to be used also depends on the down-stream processing. If the storage time of the raw milk needs to be extended before further processing, then thermisation may be used to inhibit bacterial growth (Thomas, 2000). This technique will arrest the growth of the heat sensitive micro-organisms but the nutrients of the milk are almost unchanged (Hinrichs & Kessler, 1995).

Pasteurisation

In the early days of heat treatment processes, milk was held in batches at 63 °C to 66 °C for 30 minutes (Thomas, 2000; New Zealand Dairy Board, 1996; Kessler, 1981), and then used for small-scale cheese manufacture. This process is known as the Low-Temperature Long-Time (LTLT) treatment. At the industrial scale, pasteurisation is achieved by maintaining the temperature at 72 °C to 75 °C for 15 to 20 seconds, which is called High-Temperature Short-Time (HTST) treatment. At higher temperatures, a shorter time can be used to achieve the same heat treatment. Cream and other viscous products are typically pasteurised at a temperature 3 °C to 5 °C higher than HTST milk for 1 to 5 seconds (Bylund, 1995).

The process of pasteurisation was named after Louis Pasteur who discovered that spoilage organisms could be inactivated in wine by applying heat at temperatures below its boiling point. The process was later applied to milk and it remains a very important operation in milk processing.

Pasteurisation is a thermal process applied not only in the dairy industry but in the processing of other food as well. According to the New Zealand Dairy Board (1996), the pasteurisation process is defined as:

“A heat treatment process in which every particle of the milk or liquid dairy product is heated to not less than a specified temperature and held at that temperature for not less than a specified time, then cooled to 5 °C or less or to the processing temperature if processing is to commence immediately, with the aim of avoiding public health hazards arising from pathogenic micro-organisms associated with milk and of reducing spoilage organisms associated with milk and of reducing spoilage organisms, consistent with minimal chemical, physical and organoleptic changes in the product”.

In this work, pasteurisation is defined as a heat treatment process designed to kill pathogenic organisms by heating every particle of milk to a specific temperature for a

specified period without allowing the recontamination of milk during the heat treatment process.

The aims of pasteurisation are:

1. Public health: To kill the unwanted organisms by the use of heat, making the milk and milk products safe for human consumption by destroying all bacteria that may be harmful to health (pathogens).
2. Keeping quality: To improve the storage quality of the milk and milk products by destroying the undesirable enzymes (catalase, alkaline phosphatase, lipase and peroxidase) and the spoilage bacteria. According to Kessler (1981), the shelf life of liquid milk can be up to 20 days if the storage temperature is $\leq 5^{\circ}\text{C}$.

To ensure the destruction of all pathogenic micro-organisms, the time and temperature combinations of the pasteurisation process are highly regulated. The minimum temperature and time requirements for milk pasteurisation are based on the thermal death time studies done for the most heat resistant pathogens found in milk (Kessler, 1981). As shown in Figure 4-1, the pathogenic micro-organisms are reliably destroyed under pasteurisation conditions.

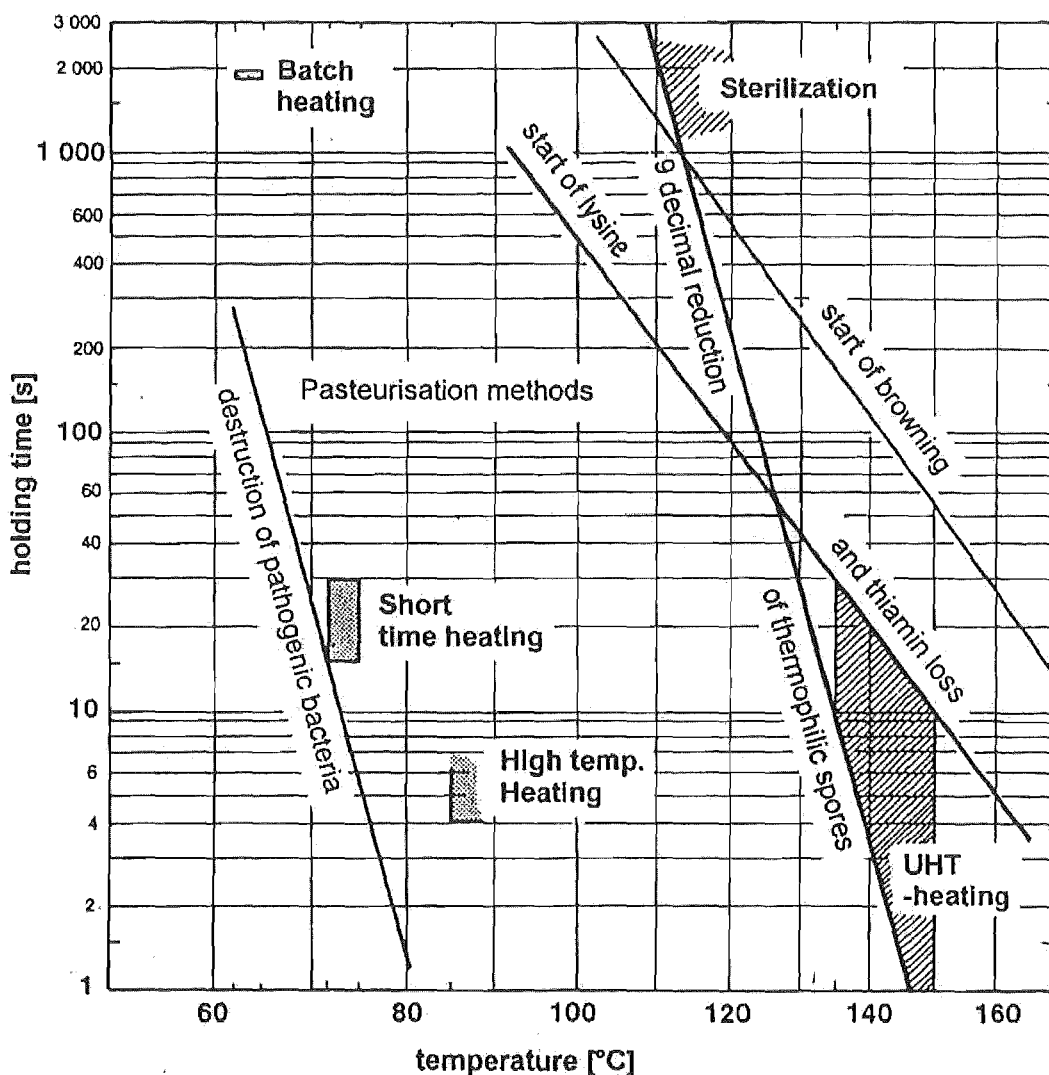


Figure 4-1 Temperature-time plots for some changes that occur in milk
(Hinrichs & Kessler, 1995).

For HTST pasteurisation, a plate heat exchanger is most commonly used, though tubular heat exchangers are also a possibility. The holding sections are normally a section of pipe long enough to ensure that the fastest particle of milk is held for the minimum time.

In addition to the general constraints on heat exchangers used for pasteurisation, there are constraints on the design and operation to ensure that unpasteurised product cannot bypass or leak into pasteurised product. This can be achieved by designing and operating the process so that the pasteurised product has a higher pressure, or by using special leak-proof plates such as the duo plate, or gaskets, round the edges of the plates and round the holes, forming the boundaries of the channels. They must also have

control systems to maintain the minimum pasteurisation and holding time, and to divert the milk from flowing forward to other processes if the required conditions are not met.

The utilities required for pasteurisation are heat supply (steam or hot water above 80 °C), cooling water or chilled water, and electricity. Figure 4.2 is a simplified representation of the feed, utilities and outlets of the pasteurisation process.

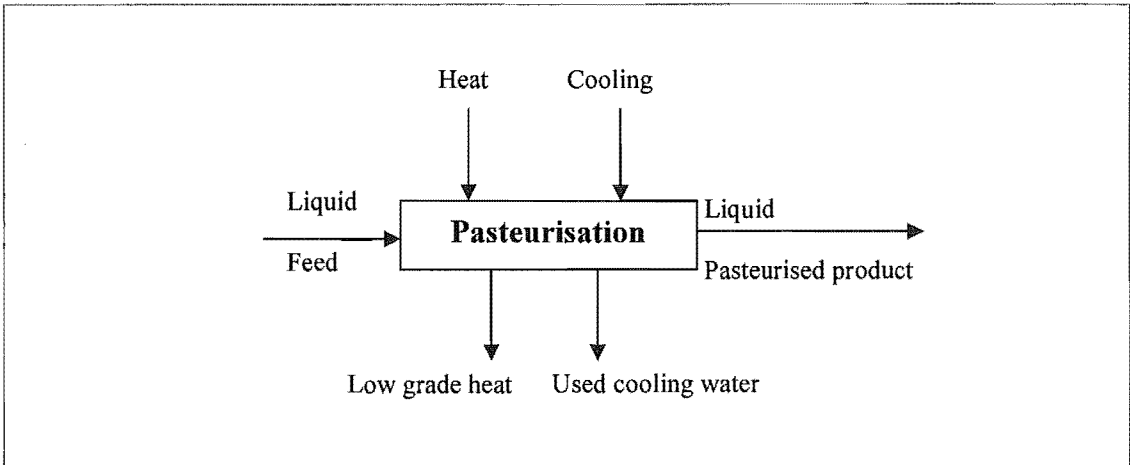


Figure 4-2 Diagram of the pasteurisation process.

In the heating and cooling process, energy can be saved by using “regeneration” (heat recovery), which utilises the heat content of the pasteurised milk to warm the incoming cold milk. Its efficiency may be calculated as follows (Bylund, 1995):

$$\% \text{ regeneration} = \frac{\text{temperature increase in regeneration}}{\text{total temperature increase}} \tag{4-2}$$

For example, cold milk, which enters the system at 10 °C, is heated to 65 °C by regeneration and then to a final temperature of 73 °C, will have a regeneration of 87.3%. The plate and tubular heat exchangers usually used for pasteurisation can achieve heat recovery of over 90% (Hinrichs & Kessler, 1995).

The high degree of heat recovery achieved by regeneration, combined with the need for very good temperature control, means that heat integration is best designed within the pasteuriser rather than between the pasteuriser and other processes.

Sterilisation

Sterilisation refers to complete inactivation of enzyme and destruction of all micro-organisms except for some heat resistant micro-organisms that survive the sterilisation process (Kessler, 1981). Any surviving micro-organisms are unlikely to grow during storage and cause product spoilage. Sterilisation can be carried out at various temperatures and holding times as shown earlier in Table 4.1.

The original form of sterilisation, in-container sterilisation at 115 °C to 120 °C for 20 to 30 minutes, is still used, for example for cans of evaporated milk (Bylund, 1995). For unconcentrated milk, ultra high temperature treatment is usually carried out by plate heat exchange, direct steam injection, or steam infusion followed by very rapid cooling and sterile packaging in glass, plastic or cardboard containers.

The milk starts to undergo a browning reaction, with a cooked or caramelised flavour due to the decomposition of lactose at 115 °C to 120 °C for 20 to 30 minutes. This is known as the Maillard reaction (O'Brien, 1997; Kessler, 1981). Flow sterilisation at temperatures of 135 °C to 140 °C for a few seconds, however, produces less discolouration and flavour change.

The use of Ultra High Temperature (UHT) treatment is preferred to sterilisation and pasteurisation, whenever a complete elimination of bacteria and spores is required for long life products.

The advantages of sterilisation is the production of high quality milk with complete enzyme inactivation (except for some heat resistant lipases and proteases), and destruction of the whole of the microflora and spore formers (except for some heat resistant spores) (Kessler, 1981). Further advantages are the reduction of processing time due to the ultra high temperature short time, and an expected long shelf life greater than 6 months without refrigeration.

The constraint is the need for sterile conditions from production to packaging. The packaging requires special attention and materials; see Section 4.7.1.

Difference between ultra pasteurisation and the UHT process

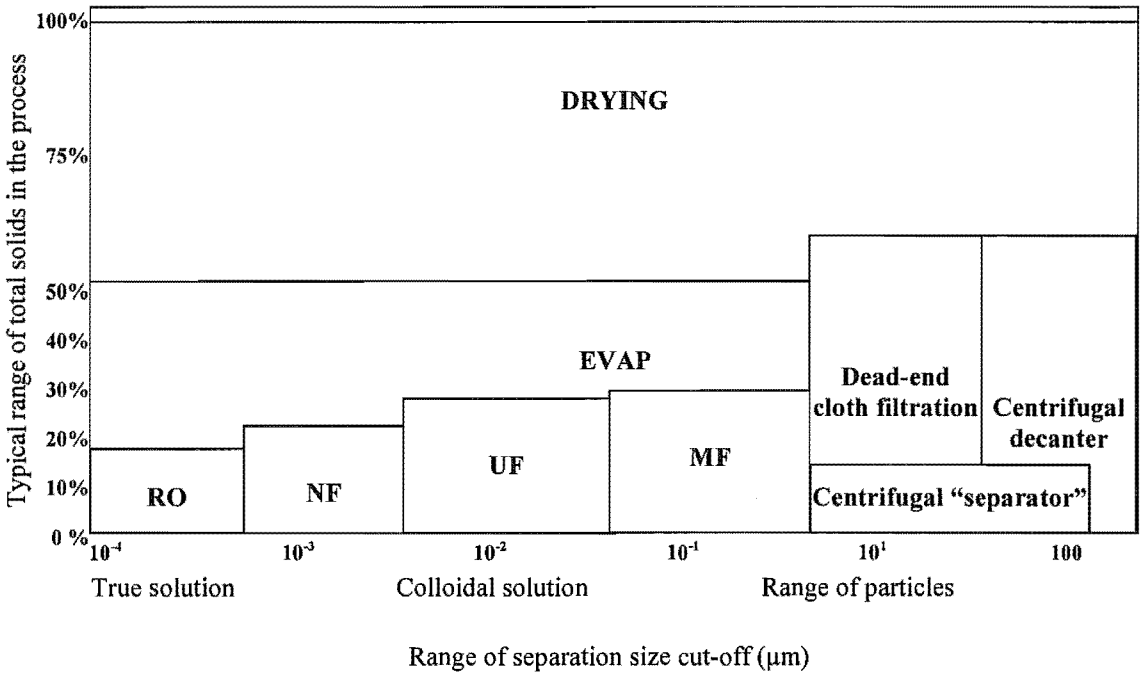
Both ultra pasteurisation and ultra high temperature (UHT) processes refer to the same process but with different holding times. Any heat treatment over about 125 °C is called ultra pasteurisation and/or UHT. Mainland Products Ltd, New Zealand runs a range of temperatures to suit the product being processed. If it is a flavoured product then a higher temperature will give a higher safety margin for sterilisation and any flavour-induced changes (Maillard reaction) will be masked by the flavour. The same kind of situation applies to vitamin-enriched products where heat treatment will destroy some of the vitamins. Typically, higher levels of vitamins must be added to allow for this.

White milks contain no additives so are generally easier to heat treat, but the flavour changes induced will be much more obvious so a suitable temperature and time combination must be found. Furthermore, certain customers like a particular flavour, for example, milk processed to UHT standard on an indirect pasteuriser compared to a direct heating process. The direct heating process heats much more quickly and produces a much reduced flavour change but certain customers did not like this “fresher” flavour and complained that the milk tasted “grassy”. The indirect heating process gives a stronger heat treatment flavour, which is more familiar to some customers (personal communication with Wylie, 2003).

4.2 Separations

Separation of one or more components from a mixture is a requirement for many operations in the food industry. Initially the term “separation” is used in the general sense, though later (Section 4.2.2) the more common specific meaning of centrifugal separation will be discussed. The aim of separation is to achieve the removal of a specific component or components, including impurities from the raw material, in order to increase the concentration of the wanted component or components of the products, which may be the residue, the extracted component or both. One application is the adjustment of the composition of raw milk to ensure that the final product is consistent from one batch to the next.

The separation processes described here are the most common in the dairy industry, namely filtration, centrifugal separation, evaporation, drying, ion exchange, crystallisation and precipitation. Some of them are shown in terms of size in Figure 4.3.



RO = Reverse Osmosis, NF = Nanofiltration, UF = Ultrafiltration, MF = Microfiltration, Evap = Evaporation.

Figure 4-3 Schematic range of separation size cut-off of some separations in the dairy industry. Boundaries are only approximates.

4.2.1 Filtration

Filtration has often been associated with the removal of solid particles from suspensions, but the size range of particles and molecules that can be separated extends from nanometres to millimetres. Figure 4-3 relates the typical range of total solids in the process to the range of separation size cut-off.

It is very useful to divide filtration into dead-end and cross-flow filtrations. Dead-end filtration is normally associated with larger particles and low solids concentrations, while cross-flow filtration is associated with fine membrane filtration with higher solids concentrations. A significant feature and constraint of both types is flux reduction from a build up of solids on the filtration medium, and fouling. These features must be considered in the design process.

In filtration, either or both streams may be the product. The product may be filtered to remove unwanted particles or molecules, or to concentrate a retained product.

4.2.1.1 Dead-end Filtration

In a dead-end filtration system (see Figure 4.4), the particles are retained on the filter medium and build up over time as a “cake”. This cake layer increases the resistance to filtration and must be removed from time to time. The filtrate passes through the media.

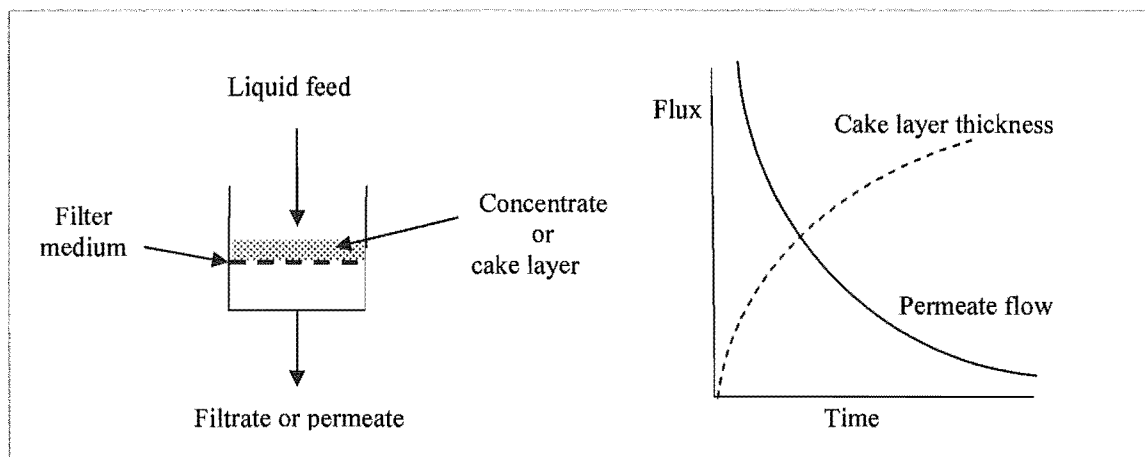


Figure 4-4 Dead-end filtration and flux decline.

Dead-end filtrations are often batch processes. Sometimes they can be run for several hours, days or months if the concentrations of particles are low. Dead-end filtration requires periodic cleaning or replacement of the filters and is usually used for separation of suspended particles larger than 10 μm . Dead-end filtration can be made continuous by using a circular or cylindrical rotary system with continuous removal of the cake.

Some of the applications of dead-end filters are:

1. Bag filters for the removal of foreign or insoluble particles from the raw milk before pasteurisation.
2. Fine mesh screens are used in the casein process to separate the curds from the whey and it is used also for separation of wash water from the casein curds. In the cheese making process, fine mesh is used to separate the curds from whey. Often these applications use cross-flow filters.
3. Filter press separation of precipitated lactalbumin from other whey components and of crystallised milk fat from liquid fat.

4. Air filters for the removal of dust and insects from dryer feed air.
5. Sintered stainless steel steam filters for the removal of rust or metal particles from steam.

4.2.1.2 Cross-flow Filtration

Cross-flow filtration is often associated with membrane filtration but a common exception is the use of screens for the separation of whey or wash water from casein or cheese curd as shown in Figure 4-5.

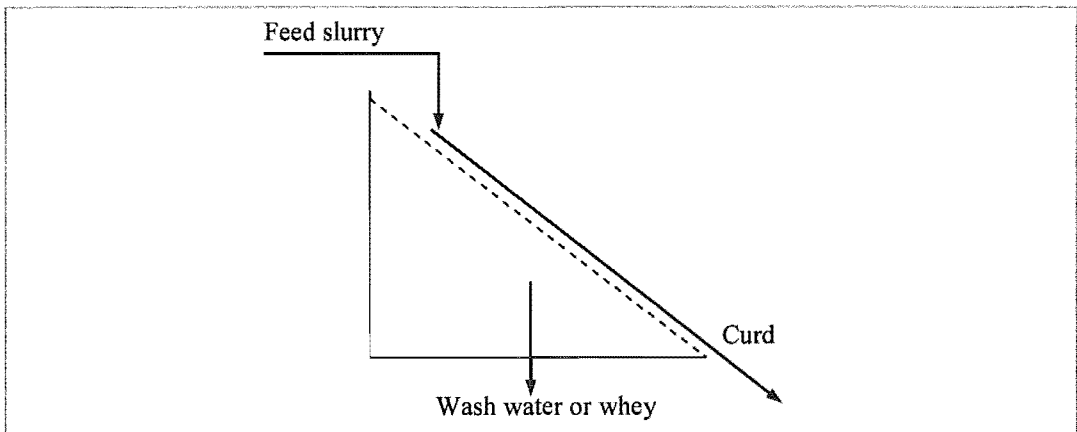


Figure 4-5 Cross-flow filtration of casein or cheese curd.

For the remainder of this section, membrane-based cross-flow filtration will be considered. A membrane is a physical barrier between two liquid systems. In over 99% of the cases of current industrial interest, the membrane is made from a polymer. This membrane-based separation process enables the separation by selectively passing one or more components of a stream through a membrane while retarding the passage of one or more other components (She, 1998). Normally the main feed under pressure is forced to flow across, parallel to, the membrane surface where the membrane rejects (retains) the large components (Figure 4-6). The retained material exits from the process, helping to reduce the contaminant build-up and the fouling on the membrane so that the cake layer remains relatively thin and the resistance to filtration remains low. To a certain extent the process is self-cleaning. This allows relatively high fluxes to be maintained over long periods of time (Mannapperuma, 1997). However, the membrane still tends to become blocked and this then causes reduced throughput and bacterial growth. Cross-flow filtration is mostly used in semi-continuous medium and large scale systems. In the pharmaceutical industry, batch ultrafiltration is very common.

One of the key advantages of membrane processing is the low temperature of the operation, which is generally below 50 °C. This makes it a highly energy efficient operation compared to other separations.

In cross-flow filtration the terms retentate and permeate are often used, and the filter medium is often referred to as the membrane.

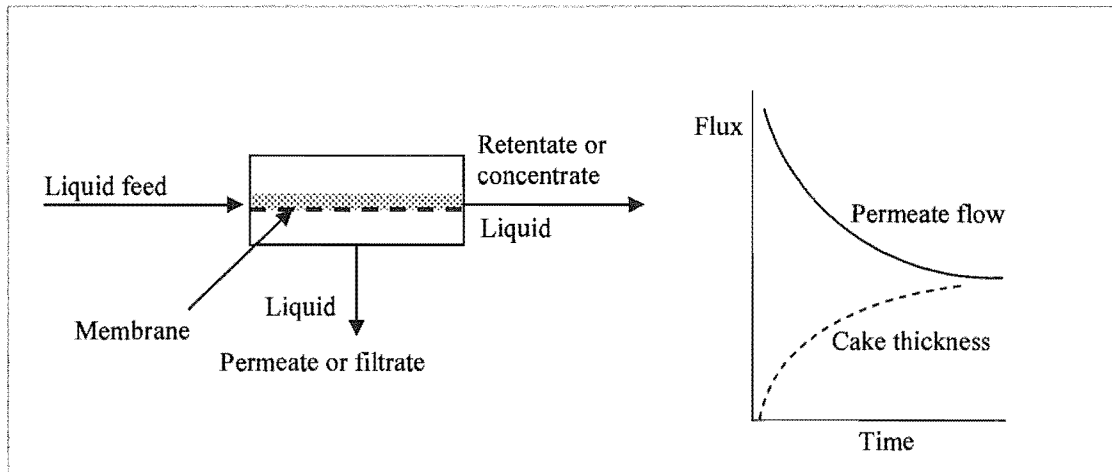


Figure 4-6 Cross-flow membrane filtration and flux decline.

A variety of commercially available membrane separation processes have been commercialised, namely microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO) and electrodialysis (ED). Most of the industrial development of membrane technologies in the food industry originate from the dairy industry and some are becoming increasingly popular in the dairy industry. This popularity is due to the simplicity of the processes, the gentle nature of the separation in which high temperature and phase changes are not required, the low energy requirements and the competitive low capital and operating costs. Usually with membranes, 25 kJ of energy are required for the removal of 1 kg of water, compared to about 500 kJ using evaporation (Sharma *et al.*, 2000). Furthermore, their compact and modular design makes the membrane separation systems easy to install and space saving.

Most membrane separations are single phase and so offer energy savings over conventional multiphase separation operations such as distillation. More importantly, the single phase separation preserves the functional properties of heat labile materials such as enzymic, biochemical and food products (Hunter, 2000).

In general, the objective of membrane filtration is the separation of large particles or molecules from smaller particles or molecules by filtration based on particle size or molecular size. This separation can be for the purification of one or both streams or for the concentration of the retentate stream. This provides a unique opportunity to separate components in liquid systems without phase change or physical and chemical change to the components (Humphrey & Keller II, 1997).

General examples are:

- Sterile filtration and purification (e.g., demineralised water by RO)
- Concentration and/or pre-concentration. For example, milk concentration, whey protein concentration by removing water and whey permeate
- Diafiltration. The desalination of a solution by the addition of a pure solvent (water). Salts and lactose are extracted during the separation process (Spreer, 1998)
- Fractionation. The separation of micro molecules, from macro molecules and small compounds (e.g., salts) in solutions.

The design steps for an empirical ultrafiltration plant (She, 1998) are the same for most membrane filtration process designs and some of those are:

By:

Selection of the membranes

The configuration of the plant.

To achieve:

The required process throughput

The required purity of the different components in retentate or permeate.

While:

Minimise the total cost

Optimise the controllability of the plant.

A variety of membrane systems are available for use in the recovery of resources and each has its own advantages and disadvantages.

There are numerous constraints on the process:

- The product must remain liquid

- The concentration is limited by the osmotic pressure difference across the membrane or retentate viscosity
- The maximum trans-membrane and cross-membrane pressure drops must be within those specified by the membrane manufacturer
- Standard membranes must be used wherever possible to ensure the availability of replacement
- The run lengths are limited to about eight hours, or perhaps 16 hours for cold processes, because of the possible bacterial growth.

A pre-requisite is that the particles, that may foul the membrane, such as cheese or casein fines, should be removed.

The utilities required for this process are electricity and demineralised water.

Decisions Factors in Membrane Separation Design

In general, the following factors affect the performance and efficiency in any membrane separation when designing.

- a) The temperature at which the plant should be operated. The temperature is one of the major influences on viscosity. Viscosity has significant effect on the permeate flux because permeate flux is inversely proportional to the permeate viscosity (She, 1998). It is mostly recommended to increase temperature as much as possible simply because the flux increases with temperature (Wagner, 2001). A larger area is required at the low temperature but microbial quality is better and the CIP costs are lower as longer run times are possible. Temperature is inversely proportional to the permeate viscosity.
- b) Feed stream chemical composition. Suspended solids represent a potential problem. Certain chemicals can degrade the polymer membrane or its supports (this is a problem of CIP chemical selection).
- c) Membrane area. The permeation rate is proportional to the membrane area.
- d) The characteristics of the membrane surface also need to be taken into consideration. These include hydrophobic, hydrophilic membrane surfaces, modified surface charge

and low protein absorption membrane surface. For example, the more hydrophilic the membrane surface is, the easier it is for water to permeate. Polysulphone membrane material has been used for UF and MF membrane in the dairy industry. The main advantage of polysulphone membrane is its exceptional temperature and pH resistance (Wagner, 2001).

- e) Yield. Many applications are controlled by the yield criteria, where there is a valuable component of interest to be recovered and its loss has economic consequences (Eykamp & Steen, 1987). In RO plants, the term “recovery” is sometimes used to mean volumetric permeate yield. Recovery refers to the percentage of feed flow that exits from the system as permeate.
- f) Cross-flow velocity. Maximum flux and minimum fouling usually occur when the velocity of feed across the membrane surface is at the maximum. Normally this is limited by the maximum cross-flow pressure drop specified by the manufacturer. To achieve a high cross-flow velocity, it is normally necessary (except for some RO processes), to recycle the retentate back to the feed.

Design calculations

Design a membrane process calculations need the following information, as a starting point, the required capacity to be treated expressed in mass flow or volume flow in kg hr^{-1} or L hr^{-1} , the composition of the feed material, the concentration ratio or volume of permeate (typically 75% to 95% of the feed volume), and the expected permeate flux expressed in mass flow or volume flow in kg hr^{-1} or L hr^{-1} and the knowledge of the physical properties of milk would be needed.

There are variety of J (flux) equations that can be found in (Mulder, 1996; She 1998).

$$J (\text{flux}) = \frac{\text{driving force (e.g., } \Delta P, \Delta C, \Delta t, \Delta T)}{\text{viscosity} \cdot \text{total resistance}} \quad (4-3)$$

where, ΔP is cross-flow pressure drop difference in bar; ΔC is component mass concentration fraction difference in kg/kg ; Δt is time difference in s and ΔT is temperature difference in K respectively.

For designing the flux, if no flux data is available, a guess must be made. If in doubt, a low flux value should be used (Wagner, 2001). Below are the recommended ranges from Wagner (2001) and the values considered in this thesis which are in brackets.

$J_{RO} = 15 \text{ to } 25 \text{ L m}^{-2} \text{ h}^{-1} \text{ (21 L m}^{-2} \text{ h}^{-1})$
 $J_{NF} = 20 \text{ to } 30 \text{ L m}^{-2} \text{ h}^{-1} \text{ (25 L m}^{-2} \text{ h}^{-1})$
 $J_{UF} = 25 \text{ to } 50 \text{ L m}^{-2} \text{ h}^{-1} \text{ (30 L m}^{-2} \text{ h}^{-1})$
 J_{MF} = There is not a general rule (13 L m⁻² h⁻¹)

Classification of Cross-Flow Membrane Separations and Their Applications

A number of different types of pressure driven membrane separation technology have been employed in the dairy process industry, classified into five main categories. These five main categories refer to the size of the pores in the membrane filter medium. Each one serves a range of specific separation functions in various sectors of the food industry, especially in the dairy industry.

Table 4-2 gives some examples of membrane separation processes used in the dairy industry.

Table 4-2 Applications of membrane separations.

Membrane type	Application
MF	Removal of bacteria from raw milk
	Separation of casein from skim milk
	Fat removal from whey
UF	Protein standardisation of milk
	Pre-concentration of cheese milk
	Whey protein concentration
	Classification of hydrolysates
	Recovery and reuse of permeate waste and brine
	Cheese brine clarification
RO	Concentration of milk
	Whole whey concentration
	Concentration of whey permeate
	Cleaning chemicals recovery
	Polishing of RO permeate and evaporator condensate
	Concentration of lactose
UF/RO	Concentration of UF permeate
	Fractionation of whey and lactose intermediates
NF	Partial demineralisation/concentration of whole whey
	Partial demineralisation/concentrate of UF permeate
	Desalting of salt whey

Microfiltration (MF)

Microfiltration (MF) designates a membrane separation process. A microfiltration membrane is classified by the pore diameter cut off, which is nominally the smallest particles that are retained, typically in the range of 0.1 to 10µm (Mannapperuma, 1997). Microfiltration requires the lowest operating pressure of all the membranes, usually less than 2 bar (Wagner, 2001). It can be used for removal of bacteria and spores without thermal treatment (sterile filtration), as well as for separation of casein from skim milk (Daufin *et al.*, 2001; Rizvi & Brandsma, 2002).

Microfiltering milk can improve the cheese yield and product consistency by concentrating the whole milk into the cheese milk (Bylund, 1995; Nordmark, 2002). This is because the retentate is concentrated in casein protein, a key component of cheese, while the permeate contains a “clean” source of whey protein and lactose that contains none of the enzymes and cultures used during cheese manufacture.

Ultrafiltration (UF)

Ultrafiltration (UF) is used for the separation of large molecules or macromolecules from a liquid phase. In the dairy industry, such large molecules are mainly proteins but UF may also trap enzymes and micro-organisms (Eykamp & Steen, 1987; Bylund, 1995; Wagner, 2001). A transmembrane pressure difference in the range of 1 to 10 bar drives ultrafiltration (Bylund, 1995).

Ideally, all the membrane pores would be of the same size, but this does not occur in practice. The molecular weight cut off is an indirect measure of the pore size (She, 1998). The molecular weight cut off is the molecular weight of the smallest molecule, 90% of which is retained by the membrane. The molecular weight cut off for ultrafiltration ranges from 1000 to 500000 (Mannapperuma, 1997). Protein and fat molecules are retained while lactose, water, and minerals pass through the membrane.

Figure 4-7 is a representation of the ultrafiltration membrane separation where diafiltration water (DF) is often employed to enhance the separation by washing out more of the permeable components (Winchester, 1996). For example, demineralised water is used to reduce the lactose and ash content to the desired level in the retentate.

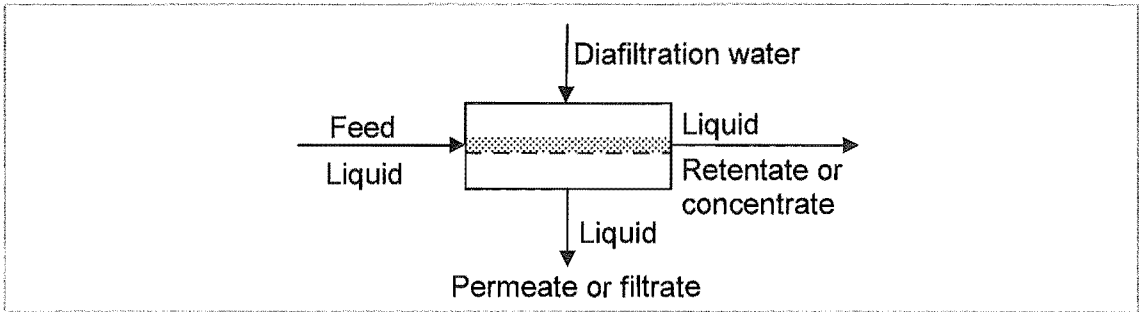


Figure 4-7 Schematic representation of ultrafiltration membrane separation with diafiltration (it also applies to nanofiltration and microfiltration).

In the dairy industry, ultrafiltration is extensively used. Uses include the protein standardisation of milk, the pre-concentration of cheese milk where whey proteins are entrapped and hence there are higher yields and higher fat recovery. Subsequently, there is less volume to process. Danish feta cheese is produced in this way. UF is also used for the classification of hydrolysates and the separation of whey protein from whey to produce whey protein concentrate (WPC) and valuable co-products. Ultrafiltration is used in the production of whey protein concentrate (WPC) to purify and concentrate whey from 0.6% protein in the feed to 80% protein in the product, and in milk protein concentrate (MPC) to purify and concentrate casein and whey protein from 3.5% in skim milk to 85% in the product.

Nanofiltration (NF)

Nanofiltration (NF) is an area of increasing opportunities in the dairy industry. It retains the solute molecules ranging from 100 to 1000 in molecular mass (Mannapperuma, 1997).

Nanofiltration is used on an industrial scale to separate mixtures of proteins and peptides on the basis of molecular weight. It is also used to achieve the mineral reduction of whey, purification and demineralisation of whey and lactose and conversion of salt whey. It is an alternative to electrodialysis. Nanofiltration uses operating pressures of 5 to 35 bar (Wagner, 2001; Mannapperuma, 1997). Diafiltration water can also be used with nanofiltration to improve the purity of the retentate product such as the desalting of salty cheese whey (Field, 1996).

Nanofiltration was recently shown to be more effective than microfiltration, ultrafiltration, decantation and centrifugation for the regeneration of an industrial alkaline solution (Dresch *et al.*, 1999). Nanofiltration is a cost effective alternative to evaporation for pre-concentration of whey up to 18% to 22% solids and at the same time removes up to 40% of the whey minerals (de Lataillade, 2003).

Reverse Osmosis (RO)

Reverse osmosis (RO), uses the tightest membrane. It can concentrate all the dissolved and suspended solids by removing the solvent, which is generally water. It is used for dewatering process streams, concentrating solutions, and obtaining potable water from effluents or from sea water. Concentration of milk by reverse osmosis prior to evaporation and cheese making has proven to be a viable membrane applications (Mannapperuma, 1997).

To achieve sufficient flux and to overcome opposing osmotic pressures, trans-membrane pressures of up to 150 bar may be necessary (Wagner, 2001) though in the dairy industry the range of 30 to 60 bar is used (Bylund, 1995). Figure 4-8 shows the schematic representation of the streams in the reverse osmosis membrane separation.

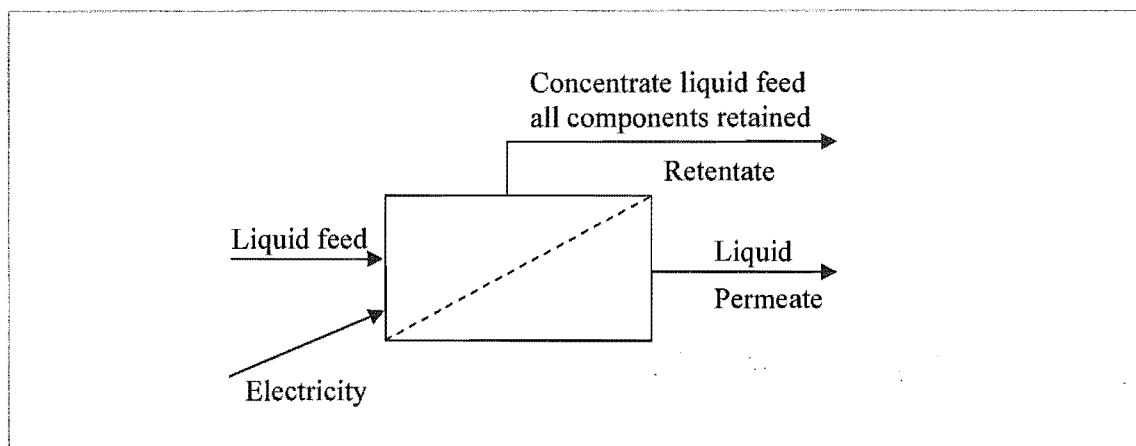


Figure 4-8 Schematic design of reverse osmosis membrane separation.

The constraints on reverse osmosis are:

- The feed must be a liquid feed with a sufficiently low viscosity to allow pumping.
- The maximum pressure in food processing is normally limited by the highest pressure hygienic centrifugal pump. Centrifugal pumps designed for the dairy industry are particularly useful because they have very “flat” characteristics. Positive pumps with pressure relief are not used because they are more expensive, and sometimes because of a tendency to vibrate that cause pulsation in the pipe system. A safety valve is needed to prevent damage to the pipe system

and the membranes. Positive displacement pumps should be avoided if not strictly necessary (Wagner, 2001)

- The osmotic pressures must be sufficiently lower than the trans-membrane pressure. The osmotic pressure of the retentate is limited to about 30 bar; this typically limits the retentate concentration to about 15% for lactose and 25% for milk total solids
- The particle size should be less than 0.1 mm only, though preferably there should be none.

The required utility is electricity.

The economics are dominated by the initial cost of membranes and then by their replacement at intervals of about 2 years (Morison & She, 2003). The cost of electrical energy can also be high due the use of high pressure pumps (Eykamp & Steen, 1987).

Reverse osmosis gives options for process integration. It provides clean water while concentrating a product or waste stream, for example:

- concentration of milk, whey, whey permeate and lactose solution with production of clean water
- recovery of water from effluent while reducing effluent volumes. There can be some leakage so permeate is not pure water but can be used for rinsing and with further treatment can be used as potable water. An example is effluent reduction when whey is recovered from casein wash water.

Electrodialysis Membrane Separation (ED)

The driving force for the electrodialysis membrane separation process is an electric field. The ions move in an aqueous solution. Ions of one charge can be removed from solution by means of synthetic polymer membrane containing ion exchange groups. For example, the anion exchange membranes carry cationic groups which repel cations and are permeable only to anions. Similarly, the cation exchange membranes carry anion groups which repel anions and are permeable to cations only. The anions and cations will migrate until they come to a selectively impermeable barrier. They will then be discharged from the cell (Howell, 1990; Glover, 1986). A schematic representation of

electrodialysis membrane separation is shown in Figure 4-9, where cation exchange membranes (K) alternate with anion exchange membranes (A) in a parallel array to form thin solution compartments (Klein *et al.*, 1987; Escudier *et al.*, 1989; Coulson *et al.*, 2002). The entire assembly of membranes is held between two electrodes that create the driving force over the whole stack. A demineralised feed solution and a concentrated brine stream solution are recovered from alternate compartments.

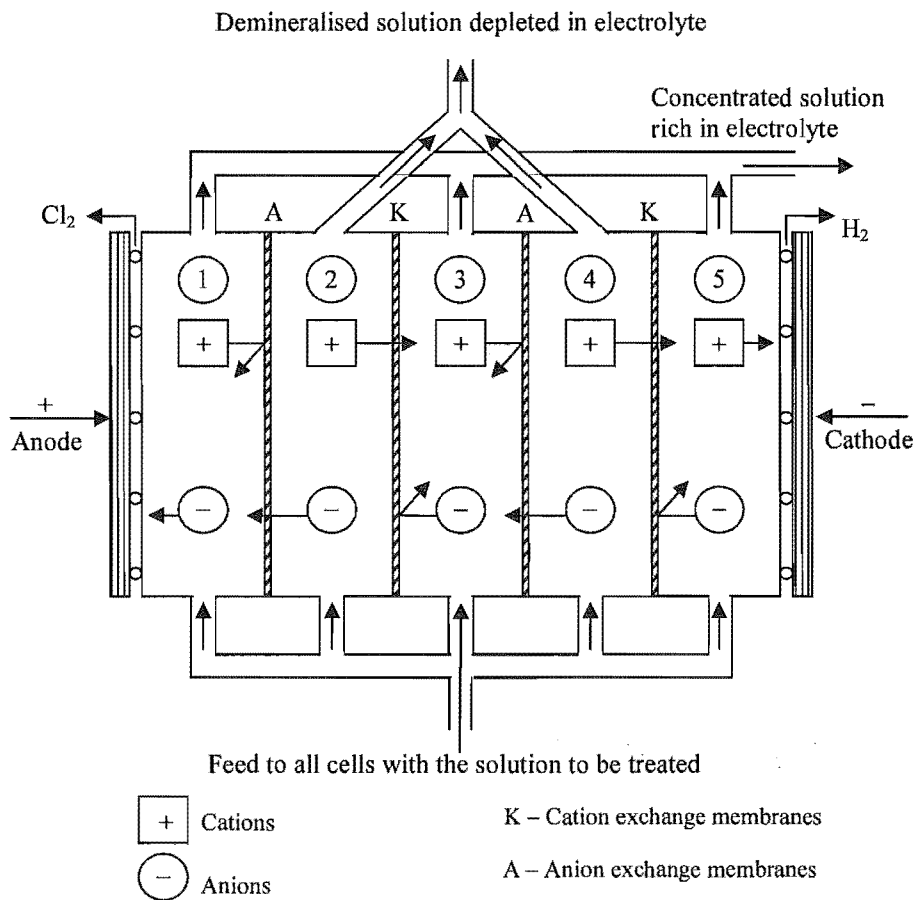


Figure 4-9 Schematic flow-diagram for an electrodialysis stack (adapted from Escudier *et al.*, 1989; Coulson *et al.*, 2002).

The system can also be set up with alternate product and dilute streams; the dilute streams carry the ions from the system while the product is being depleted of ions. Electrodialysis membrane separation is not a pressure driven process like the other membrane separation processes described above. This membrane separation is not based on size of solutes either (Mannapperuma, 1997).

The main applications of electrodialysis membrane separation have been the demineralisation of milk products and the desalination of water as widely used in sea

water desalination (Kessler, 1981; Andrés *et al.*, 1995; Mannaperuma, 1997). Some products like baby food and special diets for adults require milk demineralisation (Kessler 1981).

Electrodialysis (ED) and ion exchange (IX) processes are used in the demineralisation of whey and whey protein concentrates, where the salts have negative effects on the functionality, the organoleptic properties and the value of the final products, most of which are used in children's foods. ED and IX are sometimes combined in the manufacture of these kinds of products in the dairy industries. Electrodialysis is used first in order to demineralise until 65% to 75%, after which ion exchange is used to remove the remainder minerals. This way of operating avoids the quick depletion of IX columns. Its disadvantage is that the removal of chloride, sodium and potassium ions are accomplished by partial elimination of other desirable ions such as calcium, which must be added after the ED step (Andrés *et al.*, 1995).

Electrodialysis can be used with nanofiltration as an alternative to ion exchange in the desalting of cheese whey (Mannapperuma, 1997). Not only salt solutions may be desalted and concentrated, but also the acids. More recently, ultrafiltration, reverse osmosis and nanofiltration have been used in preference to electrodialysis for similar applications. For example, UF (Morison, 2003, personal communication) and NF (Wagner, 2001) have been used for desalting salt cheese whey.

Environmental Applications of Membrane Separation

Membrane separations offer opportunities for reduction in effluents streams by concentration of effluent or by waste minimisation. Membranes can be used for water recovery since the discharge of millions of litres per day are typical in the dairy industry. There are tight environmental constraints on the allowable quantity and quality of water discharged to land or waterways. The minimisation of volume and suspended solids can be critical to the economics of projects. Even a low grade and relatively low value by-product can be less of a cost than a dilute waste stream. Water recovery and production of by-products are the challenges for a process design methodology.

Examples of opportunities include:

- RO concentration of effluent while producing clean water. This can reduce the liquid load and storage requirements in effluent treatment or disposal systems.
- RO concentration of casein wash water producing a valuable animal feed and demineralised water
- RO concentration of any milk based stream to reduce evaporation energy requirements while producing demineralised water
- NF or UF removal of solids from used cleaning solutions to enable chemical reuse.

The water produced from RO plants is clean enough to be used directly in cleaning systems, but not for the final rinse.

4.2.2 Centrifugal Separations

Centrifugal separation is a process that enhances settling by applying centrifugal acceleration. It enables the slow batch process of gravity separation to be replaced by a much faster continuous process. High centrifugal forces are applied. For example, a separator that is used for decreaming rotates at 6000 rpm to 7000 rpm (Spreer, 1998).

It is used in the dairy industry for the separation of fat from milk and whey, for removal of solid contaminants from milk, and for the separation of slurries such as casein curds and whey.

Both gravity and centrifugal separation processes are governed by Stoke's law which for gravitation settling is:

$$V_g = \frac{d^2(\rho_p - \rho_l)}{18\eta} a \quad (4-4)$$

where:

V_g = particle settling or flotation velocity [m s^{-1}]

d = particle diameter [m]

ρ_p = particle density [kg m^{-3}]

ρ_l = density of the continuous phase [kg m^{-3}]

a = acceleration from gravity or centrifugal action [m s^{-2}]

η = viscosity of the continuous phase [$\text{kg m}^{-1}\text{s}^{-1}$]

From the equation, it is clear that the particle sedimentation velocity increases by:

- Increasing the particle diameter
- Decreasing the viscosity of the continuous phase
- Increasing the difference in density between the two phases
- Increasing a .

Centrifugal separations according to physical conditions

The most common liquid-liquid separation is that of fat, as cream, from whole milk. Fat globules have a wide size distribution and the small globules move slowly and are difficult to separate. In practice separation of fat globules less than approximately $1\text{ }\mu\text{m}$ is difficult under normal conditions. In commercial operations, the milk serum phase (skimmed milk) usually has a fat content in the range of 0.04% to 0.06% (Lewis, 1986b; Towler, 1986), though Bylund (1995) gives 0.09% fat content.

Liquid-solid separation can be achieved using a clarifier, decanter, filter-screening centrifuge or hydrocyclone. 'Clarifier' is the term used to describe a centrifugal separator with a vertical axis and which is designed to remove small fractions of particles. The solids are discharged as a slurry. For example, clarifiers are used to remove the cheese fines from the whey and foreign material from raw milk. Bactofugation (e.g., Bactofuge offered by Tetra Pak) is used by many companies such as a United States specialty cheesemaker. Bactofugation is a mechanical reduction of bacteria. Bactofuge is installed in series with the centrifugal separator, either downstream or upstream of it and the same temperature is often chosen, i.e. typically $60\text{ }^{\circ}\text{C}$ to $63\text{ }^{\circ}\text{C}$ (Bylund, 1995). A Bactofuge is an example of a clarifier used for removal of microbes based on their higher density, specially for spore-forming cells or spores, as they have higher densities. It enables almost complete separation of this group of micro-organisms (Spreer, 1998). It is also used now to improve the bacteriological quality of milk intended for other products like cheese, milk powder and whey for baby food.

‘Decanter’ is the term used to describe a centrifugal separator with a horizontal axis, which is designed to separate slurries containing a high fraction of solid material. The solids are normally discharged as a “dry” material. Applications include separation of lactose crystals from “mother liquor” and separation of casein curds from wash water. The decanters used in the dairy industry are the decanting centrifuge or the conveyor-bowl centrifuge.

Hydrocyclones rely on the rotation of the fluid to produce centrifugal acceleration which separates solid particles. The fluid viscosity must be low enough, and density difference high enough to allow separation with relatively low acceleration.

Centrifugal liquid-gas separation uses hydrocyclones and deaerators. Applications include the separation of air from the incoming whole milk by a deaerator with tangential feed, and separation of vapour from concentrate in a milk evaporator. In this second application the vessels are normally known simply as “separators”.

Centrifugal gas-solid separation is carried out in cyclones, a typical example being the separation of air from milk powder after spray drying.

4.2.3 Evaporation

Evaporation is the removal of solvent in the form of vapour from a solution or slurry. For the majority of applications, the solvent is water. Evaporation often overlaps the operations of distillation, drying and crystallisation (Minton, 1986). The main objective of evaporation in the dairy industry is to remove water in order to increase the solids content of the liquid milk products containing dissolved, emulsified or suspended constituents.

Evaporation finds wide applications in the dairy industry, such as to concentrate milk, whey proteins, and lactose prior to drying. Typical applications of evaporation are to:

1. Reduce the bulk volume for storage or transport
2. Improve the shelf life

3. Change the product chemically or physically into a form more suitable for some end uses
4. Increase the product viscosity
5. Minimise the drying energy requirement. From the point of view of expenditure of energy, it is more economical to dry the previously concentrated products
6. Concentrate for a subsequent crystallisation process, e.g., in lactose production
7. Concentrate to reduce volumetric flow, e.g., for a subsequent ion exchange process.

Table 4-3 also shows the moisture content for evaporated milk with two different fat compositions and for milk products like skim milk, buttermilk and whey which are going to be subsequently dried to produce milk powders (Kessler, 1981; Hall & Hedrick, 1971). A moisture content of 50% to 60% is needed for milk products which are going to be subsequently dried to produce milk powder.

Table 4-3 The final moisture content of some milk products after evaporation (Kessler, 1981).

Product	Products moisture content		Totals solid
	Before	After	TS%
Evaporated milk 10% fat	87%	67%	33%
Evaporated milk 7.5% fat	87%	75%	25%
Whole milk	87%	50-60%	50-40%
Skim milk	91%	50-60%	50-40%
Buttermilk	90%	50-60%	50-40%
Whey	94%	50-60%	50-40%

For many years now the tubular falling film evaporator has been the main type of evaporator installed in the dairy industry. These and other common types of evaporators have been described by several authors (e.g., Minton, 1986; McCabe *et al.*, 1993).

Table 4-4 shows heat evaporation of water and approximate energy requirements in some processes to remove water.

Table 4-4 Approximate energy requirements in some processes to remove water
(Waslra *et al.*, 1999)

Heat of evaporation of water and Processes to remove water	Heat of evaporation kJ/kg of water removed	Energy requirements kg steam/kg of water removed
Single stage evaporation of water at 40 °C	2405	1 kg steam
Evaporation, 3 stages	~ 800 ^a	0.35 kg steam
Evaporation, 6 stages, with TVR	~ 230 ^a	0.1 kg steam
Evaporation, 1 stage, with MVR	~ 115	0.05 kg steam
Roller drying	~ 2500 ^a	1.1 kg steam
Spray drying	~ 4500 ^a	2.0 kg steam
Reverse osmosis	20-35	

^a Excluding mechanical energy, i.e., pumps.

Without any energy saving features, evaporation requires a large amount of energy, so energy reuse is normally required. Good energy economy is obtained by the recompression of the vapour produced either by thermal vapour recompression (TVR) using a steam jet, or by mechanical vapour recompression (MVR) using a fan (Knipschildt, 1986; Umeda *et al.*, 1978).

All are controlled by the fundamental heat transfer equation

$$Q = UA \left(T_{\text{steam}} - T_{\text{milk}} \right) \tag{4-5}$$

The heat transfer coefficient, *U*, can be obtained from correlations (see Winchester, 2000). The temperature driving force from the steam to the milk is typically 4 °C to 8 °C. The evaporator area, *A*, is calculated from this equation. Fouling decreases the overall heat transfer coefficient by introducing additional resistance. Since the area of the evaporator is fixed, the heat transfer can only be increased by increasing the driving

force, so the steam temperature must be increased. This however tends to increase the rate of fouling.

Design Specifications

The evaporator must be designed to increase the total solids (TS) of a specified feed to a specified product concentration at a specified throughput. The evaporator must have sufficient surface area to achieve the required amount of evaporation. The final total solids content achieved must meet the specifications of the following process step or of the product. In cases where drying follows, high total solid contents are desirable to maximise energy efficiency, and to give the desired particle characteristics.

Based on the conservation of mass

$$\dot{m}_{\text{feed}} x_{\text{feed}} = \dot{m}_{\text{conc}} x_{\text{conc}} \quad (4-6)$$

or

$$\dot{m}_{\text{conc}} = \dot{m}_{\text{feed}} \frac{x_{\text{feed}}}{x_{\text{conc}}} \quad (4-7)$$

and

$$\dot{m}_{\text{evap}} = \dot{m}_{\text{feed}} \left(1 - \frac{x_{\text{feed}}}{x_{\text{conc}}} \right) \quad (4-8)$$

Where \dot{m} is mass flow rate of the solution in kg s^{-1} and x is mass fraction. The evaporation mass flow rate is the difference of the feed and the concentrate flow rates.

Constraints on operation and design of evaporators

It could be said that the design of evaporators is driven by the constraints as much as the design specification. A number of constraints are given below, grouped into different types. The constraints naturally lead to the practical requirements that the process should be continuous.

The flow rate through each tube must be above the minimum flow rate that is required to completely wet the tube, otherwise, low heat rates of heat transfer and excess fouling will occur (Paramalingam *et al.*, 2001).

Constraints of the product on the evaporation process

- Residence time must be minimised because of the potential thermal damage of milk
- The temperature should be kept below approximately 70 °C as the protein can be damaged (denatured) by higher temperatures and rapid fouling then occurs (Winchester, 2000)
- Fouling typically prevents the evaporation from running for more than about 20 hours continuously
- Areas of liquid hold-up must be avoided as bacteria can grow at most of the temperatures that exist in an evaporator
- Product cannot be recycled as this can increase bacterial growth.

The constraints of the process on the product

- One important operational constraint is falling film breakdown (Winchester, 2000). Film breakdown is the condition where a thin liquid film fails to wet completely the falling film evaporator surface. This is usually exhibited by the formation of dry spots in the flow (Bohn & Davis, 1993). These dry spots break down into a series of rivulets in which the full upstream flow is conveyed into thin fingers of liquid (Ponter *et al.*, 1967; Trela, 1994; El-Genk & Saber, 2001). The result is reduction of contact area and mass transfer, and thus reduces evaporator efficiency (Kessler, 1981; Hoke & Chen, 1992). This constraint of the process on the product has been the object of many investigations (Hartley & Murgatroyd, 1964; Lyu & Mudawar, 1991; Penn *et al.*, 2001; Michalski & Briard, 2003).
- The feed must be liquid with a sufficiently low viscosity to allow pumping.

The utilities required for evaporators are steam, electricity and cooling water but the amounts of each is very dependent of the type of evaporator chosen.

Although evaporation is a very efficient operation due to the heat recovery in multi-effects evaporators, it is not as energy efficient as membrane processes. In some cases a combination of membrane separation followed by evaporation can be capital and energy

efficient. Given the large amounts of energy and water used or generated, evaporation is a good candidate for heat integration, heat recovery and water (condensate) recovery.

4.2.4 Drying

Drying or dehydration is one of the major processes for food preservation used worldwide for centuries. Drying is the removal of water or other volatile liquids from a liquid, slurry or wet solid. The removal of liquid by thermal drying could be more costly than by mechanical separation techniques (Sinnott, 2000). The drying process influences the quality of the final product (Crapiste & Rotstein; 1997; Walas, 1990). Drying has the highest energy requirements per ton of finished product of all commonly used dairy processes (Knipschildt, 1986).

There are several reasons for converting liquid food products (e.g., milk) into powders. The three most important reasons are:

1. The removal of the medium (water) that promotes the growth of pathogens produces a durable product (i.e., improved shelf life).
2. Reduction in weight and volume lower the cost of transportation and storage.
3. The product needs to be changed chemically or physically into a form more suitable for some end uses.

Types of Drying in the Dairy Industry

Two drying methods are used more frequently than others in the dairy industry. The first method is spray drying. The air temperature that spray driers require is in the range of 150 °C to 200 °C (Kessler, 1981). The second method is fluidised bed drying. In a fluidised bed drier, the solid particles are maintained suspended against gravity in an upwards-flowing air stream. A fluidised bed drier can be connected to the bottom of the spray drying chamber and can be vibrated by a motor to convey the powder along the length of the drier (Bylund, 1995). There may also be a horizontal component in the airflow to convey the milk material through the drier (Earle, 1983). Fluidised bed drying uses steam, hot air and cold air. The air temperature that these driers require is in the range of 50 °C to 130 °C (Kessler, 1981).

Spray driers convert liquid feed to solid product, generally in two stages. They are fed with liquid with 45% to 50% total solids content (TS) and dry this to about 93% TS. Then the fluidised bed drier takes the solid feed and dries this to the final dried product containing perhaps 96% TS.

From the energy point of view driers are less energy efficient than evaporators (Earle, 1983). In situations where the moisture has been significantly reduced, fluidised bed driers become more efficient than spray driers in removing the remaining moisture. In addition the capital and maintenance cost are low because of their simple design with few moving parts (Crapiste & Rotstein, 1997).

Spray Drying

This process involves the pumping of feed to a rotary or pressure atomiser thus converting the liquid into a spray of droplets. The droplets are directed into a controlled flow of hot drying air, and rapid moisture evaporation from each droplet occurs. As moisture is removed, each droplet forms a particle. High viscosity milk concentrates seem to have several detrimental impacts on the operation of the spray drier. The spray particles from the spray drier nozzles are larger, causing larger powder particle sizes. The particle evaporation mass transfer and heat transfer coefficient are low and these cause the spray particles to have a higher moisture content.

There are four stages involved in spray drying:

1. Atomisation. The objectives of the atomisation are to form spray droplets with a consistent size distribution but with a sufficiently wide range to give high bulk density with a low proportion of fines. Uniform particles provide superior instantising products, reduced product losses and less over-drying and under-drying.

A consistent feed viscosity, and hence total solids content, is required to give consistent atomisation and particle properties. Total solids content should be high, for energy efficiency and because low feed viscosity gives fine powder with an undesirable low bulk density.

2. Hot air contact. There are three forms to hot air contact, co-current flows, counter-current flows and mixed flows (Kessler, 1981). For spray drying of milk powders co-current flow is always used as this leads to lower product temperatures. The air for drying is filtered and heated before it contacts the atomised product (Hall & Hedrick, 1971).

3. Evaporation. Only a short period of time is necessary to complete the removal of moisture and for the particle to acquire its final shape and structure. Typical residence times are 5 to 10 seconds.

4. Product recovery. This involves the separation and recovery of the dry milk particles from the drying air leaving the chamber. The powder is recovered from the base of the drying chamber and from the associated collectors such as cyclones (Zhao, 1999) or bag filters.

All of these four main process stages have an effect on the final properties of the product, such as the mean particle size, bulk density, “flowability” and visual appearance (colour).

Design calculations

Design calculations need the following information, as a starting point, the required capacity expressed in mass flow in kg hr^{-1} or volume flow in L hr^{-1} , the composition of the feed material, the required total solids content for the product, product specification and the knowledge of the physical properties of milk would be needed. Drying is basically a heat exchange operation and rate of transfer follows the normal type of equations.

Energy efficiency of spray driers

The moist air from the spray dried cannot be reused. So, it is discharged to the atmosphere. One measure of the energy efficiency of a drier is given by equation 4-9 (Winchester, 2000).

$$\text{Eff} \approx \frac{(T_{\text{in}} - T_{\text{out}})}{(T_{\text{in}} - T_{\text{amb}})} \quad (4-9)$$

where:

T_{in} = temperature of hot inlet air (°C)

T_{out} = temperature of discharged air from spray drier (°C)

T_{amb} = temperature of ambient air entering the spray drier (°C)

A typical spray drier working with milk will use steam heated air of approximate 200 °C and will discharge the air at 60 °C with an ambient temperature of 25 °C (Winchester, 2000).

Computational fluid dynamics (CFD) has become a real design tool that can provide a description of the patterns of flow and droplet movement in the drying chamber. This helps the understanding of air flow and the interaction with the atomised droplets. Considerable work has been performed recently in computational fluid dynamics, which enables considerable insights into the detailed design of spray drying chambers by Oakley & Bahu (1993). Particular applications include tighter design of spray driers and reducing operational problems, such as wall deposition. Langrish & Fletcher (2001) have reviewed particular issues in the use of spray drying for food ingredients. These include aroma loss, thermal degradation and particle stickiness. They have demonstrated that CFD techniques give useful predictions of the deposition of particles on walls and have used this knowledge to design preventative measures.

One of the problems of spray drying is powder adhesion on the walls and roof of the spray drier. These deposits are unwanted because they become burnt, thus degrading the powder quality. Then they must be removed by washing, which causes down-time and production of effluent. Fires and explosions are the main hazards in a drying operation (Crapiste & Rotstein, 1997). Wall depositions not only reduce quality and yield, but it may also pose a potential fire risk and compromise hygiene requirements (Langrish & Fletcher, 2001). Overheating of the spray drier particles appears to be the cause of the product milk powder burning (Winchester, 2000). Various design ideas have been introduced over the years to prevent or remove deposit formation, like brooms, secondary air flows, and scrapers. In spray driers, the particle motion is highly

complex as millions of particles move in a local environment of continually changing temperature and humidity. Often designing flexibility into the spray or air flow direction enables subsequent adjustment to minimise wall adhesion.

Others Types of Drying

Others types of drying that could be used in dairy processing are freeze drying and roller drying. Freeze drying concentration involves freezing the product followed by sublimation of water vapour under a high vacuum. Suitable temperatures and pressures must be established in the drier to ensure that sublimation occurs (Earle, 1983). In freeze drying there is no heating damage. The food structure is better maintained under these conditions but this process has not been developed for large scale processing (Varnam & Sutherland, 1994; Garcia *et al.*, 1999).

Roller drying involves spreading the feed over the surface of a heated roller. The roller rotates and after less than a single rotation, the water in the milk evaporates and dried milk falls or is scraped off from the roller and is ground into flakes. It is not popular because of its relatively small scale, the mechanical complexity and the form of the product. Roller drying can only be used for liquid products, which can either have a low viscosity or be highly viscous to paste-like (Kessler, 1981). A large part of roller dried whole milk powder is destined for chocolate manufacture because milk fat is generally added to milk chocolate in the form of crumb (Kaylegian & Lindsay, 1995).

4.2.5 Ion Exchange

Ion exchange is a low temperature separation process in which specific ions are adsorbed from solution onto ion exchange resins. It is typically a high cost separation reserved for high value products. For this economic reason, it is not often used in the dairy industry (Kessler, 1981). It is a very well known demineralisation technology. It has the ability to remove almost all of the ions in whey and permeate (Hoppe & Higgins, 1992) and can also be used to separate charged proteins from solution.

Ion exchange of whey protein concentrates are being used commercially to produce low fat products known as whey protein isolates (Etzel, 1995; University of Guelph, 2003). Ion exchange is also used for the removal of calcium from milk (Holsinger, 1997). The

calcium phosphate crystals recovered by this process can be marketed as milk minerals (de Lataillade, 2003). The most important applications are the softening (calcium removal) of water, industrial process water demineralisation for boiler feed water and other process water, material recovery from industrial waste water and whey protein fractionation. An extensive history of ion exchange treatment exists in the metal industry (recovery of precious minerals, e.g., gold, uranium, copper and silver), recovery of common metals and heavy metal removal (Dietz, 1996; Wankat, 1990).

Ion exchange is used for whey protein fractionation. An example of whey protein fractionation is the isolation of β -lactoglobulin and α -lactalbumin by eluting from a cation exchanger and using different pH values for eluting the proteins as separate fractions without using salt elution (Etzel, 1999). Methods of separating and recovering proteins from a protein solution with the preselected ion exchanger have been described (Ayers *et al.*, 2003).

An appropriate resin must be selected for the process. Resins are normally classified as cation resins (used to remove cations from solution) or anion resins (used to remove anions). Cation resins will typically exchange H^+ or Na^+ ions for the divalent cations Ca^{2+} , Mg^{2+} or similar ions while anion resins typically exchange OH^- ions for anions like Cl^- .

Ion exchange resins are insoluble polymers and they are usually packed into beds through which the liquid flows. After the resin has been “exhausted” it must be regenerated by adding an appropriate high concentration solution. The two-stage nature of this process requires that ion-exchange almost always be a batch process.

The first ion exchangers used natural zeolites. The first known ion exchanger occurred in inanimate soils, sands and rocks and in living organisms (Helfferich, 1962). The popularity of ion exchangers has grown over the last few decades and many synthetic ion exchangers have been developed (Ruthven, 1997; Bolto & Pawlowski, 1987). The more common are synthetic zeolites and polymeric ion exchangers (Jorgensen, 2002).

Today the ion exchanger is firmly established as an unit operation and is an extremely valuable supplement to other procedures such as filtration, distillation and adsorption.

4.2.6 Crystallisation

Crystallisation is employed heavily as a separation process in the chemical industry, particularly where salt are recovered from aqueous media and also used to recover product, to refine intermediate chemicals and to remove undesirable salts (Moyers & Rousseau, 1987; Wankat, 1990). Crystallisation is one of the oldest of unit operations and is used to produce sodium chloride and sucrose. It can be used as a purifying process and of providing crystalline materials in a desire size range (Coulson *et al.*, 2002).

Crystallisation is a crystal solidification of some components from a vapour, solution or molten solid (Perry *et al.*, 1998). In the dairy industry, crystallisation takes place in the liquid solutions and in the molten solid, though only crystallisation in the liquid solutions in considered here.

A well formed crystal itself is nearly pure, but it retains “mother liquor” when removed from the slurry. The impurities of the crystallisation process need to be washed out using clean solvent water. In practice, much of the retained mother liquor is separated from the crystal by filtration or centrifuging (McCabe *et al.*, 1993). Crystallisation is rarely the last stage in a process and solvent separation, washing and drying stages are usually required (Coulson *et al.*, 2002). For example, crystallisation is used for the production of lactose crystals (Holsinger, 1997).

Crystallisation requires much less energy for separation than distillation or other commonly used methods of purification (Coulson *et al.*, 2002). In addition, crystallisation can be carried at low temperatures and on a scale, which varies from a few grams up to many tons per day (Perry *et al.*, 1998).

Crystallisation Constraints

- Crystallisation is a slow process
- Feed must be completely dissolved
- Mother liquor adheres to the crystals and requires washing to purify the product.

4.2.7 Precipitation

Precipitation is a separation in which a solid substance is produced in a liquid solution by forming an insoluble product. Woods (1994) considers protein precipitation as a coagulation process, but the term used in this study is a precipitation process.

Examples in the dairy industry include precipitation of calcium phosphate by increasing the pH above about 7.4, precipitation of alpha-lactalbumin by heating, and precipitation of casein by acid or enzyme treatment.

Casein is precipitated either by acids reducing the pH to about 4.7 or by cleaving part of the protein with an enzyme while the whey proteins remains in solution, in both cases allowing casein molecules to coagulate.

4.2.8 Reverse Micellar Separation

Reversed micellar methods offer the potential for continuous extraction of specific proteins from an aqueous mixture, thus achieving simultaneous concentration and purification of specific proteins in an efficient manner. This method uses reverse micellar solvents to achieve protein specific isolations of α -lactalbumin (α -LB) and immunoglobulin (IgB) due to the charge-charge interactions, the hydrophobic effects and the size of the protein relative to the droplets. The reverse micellar solvent contains small droplets of water that are stabilised within an organic solvent by a surfactant. Because the protein molecules often move from an original water phase into these small-encapsulated water droplets, reverse micellar extraction is an attractive approach for separating proteins from an aqueous solution.

California Dairy Food Research Laboratory Center in Davis has successfully separated β -lactoglobulin (β -LG), α -lactalbumin (α -LB) and immunoglobulin (IgB) using reverse

micellar droplet phase technology making use of charge-charge interactions and hydrophobic effects and the size of the protein relative to the droplet (Dairy Management Inc., 2000).

β -LG and α -LB have desirable functional properties when used as food ingredients, including the ability to stabilise food emulsions and foams, not to mention the ability to create protein-based gels. Both of these proteins, as well as IgB, are valuable for their nutritional qualities and for their possible development into pharmaceutical products (Dairy Management Inc., 2000).

However despite many years of research, reverse micelle separation is not used commercially.

4.3 Mixing or Blending

Blending refers to the intermingling of miscible fluids to produce some degree of uniformity. Mixing involves the production of uniformity between materials that may or may not be miscible. Mixing and blending are synonymous for miscible liquids. Agitation is the most general term, involving the production of fluid motion for blending, mixing, heat transfer, and mass transfer (Stephenson & Blackburn, 1998; Rielly, 1997).

Mixing or blending can be defined as “the operation of combining liquid components of different viscosities and or densities to produce an end product with uniform properties throughout, such that the final product will not separate into component phases with time” (McDonough, 1992). Regardless of the type of blending applications, this process requires an understanding of the characteristics of the material, the starting conditions, the blend time that the process requires, the tank dimensions and the required degree of uniformity. Miscible liquids are blended in the relatively small process vessels by centrally mounted propeller or turbine impellers, or by side-entering propellers in large vessels, and by jet mixers (McCabe *et al.*, 1993).

Mixing is used for combining different products or for the addition of some ingredients such as vitamins, flavours, fruits and others to enhance the nutritional value of products. There are several mixing process applications in the dairy industry. For example, traditionally the milk fat component is standardised by separating the fat from the milk. The fat is added back at a controlled rate to give a specific fat content in the product. Protein may also be standardised where the specifications allow, by adding lactose to reduce the protein: lactose ratio prior to fat addition. Mixing can be done in-line or by batch mixing in tanks designed to suit the specific application.

There are specifically designed processes with mixed fats products where vegetable or other animal fats replace the milk fats. Consistency is improved by adding vegetable fats because the melting point is reduced and very good spreadability is achieved at refrigerator temperature (Spreer, 1998).

There are two major types of blending and they are:

1. Wet blending. At least one of the components must be liquid or contain high moisture, for example, the standardisation process described in Section 6.2.3. This can include dissolution of powders in liquid, or mixing to produce a solid liquid slurry.
2. Dry blending. All of the ingredients are dry and must be miscible to obtain uniformity. Generally, solid-solid mixing is referred to as 'dry blending' in the dairy industry, for example, the blending of dry powders for the formulation of baby food.

4.4 Homogenisation as a Special Case of Size Reduction

Size reduction operation such as solid grinding, liquid emulsion, colloid mill and homogenisation are size reduction operations.

In homogenisation, the milk is exposed to a short period of intense input of mechanical energy, which breaks the milk fat globules into small globules and disperses them

through the milk. As a result, a homogenous dispersion of fine fat globules throughout the milk is achieved. This process operation prevents the formation of a layer of cream at the top of the milk if the milk is left to stand. The objective is to reduce the size of fat globules.

Homogenisation is also done with other purposes, for example, to improve flavour, to increase viscosity, to give a stable gel in yoghurt and to reduce fat separation in ice cream during freezing (Kessler, 1981).

The homogeniser process technology can be purchased off-the-shelf from a supplier rather than designed by the process designer.

4.5 Reaction

Reactions in the dairy industry include:

- Fermentation of lactose to produce lactic acid
- Enzyme hydrolysis in cheese and rennet casein manufacture
- Enzyme hydrolysis of proteins to produce hydrolysed protein
- Hydrolysis of protein as part of cheese ageing
- Hydrolysis of lactose
- Solubilisation of casein with hydroxides.

Fermentation is the oldest method for preserving milk and it developed independently in different parts of the world. The responsible micro-organisms differ and the differences are reflected in the types of cultured milk that they produce (Walstra & Jenness, 1984). Lactic acid aids in cheese curd formation by reducing the electrical charge on the protein, acts as a preservative in cheese, butter and yogurts by reducing pH to a level that prevents unwanted bacterial growth, and contributes to acid flavour of cheese (McSweeney *et al.*, 1997). The reaction is also used for lactic acid casein production in which the pH is reduced to the isoelectric point of casein (pH 4.7), i.e., reducing the electrical charge to zero, and enabling coagulation (Walstra & Jenness, 1984) and precipitation of the casein.

The most important reaction in the dairy industry is of the milk proteins, which involves destabilisation of the protein micelles. In some cases, these are technologically desirable reactions, such as formation of a gel either when the pH of the milk is reduced (e.g., manufacture of fermented milks and acid-set cheese), or when κ -casein undergoes selective proteolysis (e.g., manufacture of cheddar cheese). Other enzymes continue flavour development during ageing.

Sodium, calcium and ammonium caseinate are produced by the reaction of acid casein with the corresponding hydroxide, producing a soluble casein-based product that is usually spray dried.

4.6 Storage

Storage is required in many parts of the process. The combination of temperature and holding times in the storage is very important. Low temperatures ($<10\text{ }^{\circ}\text{C}$) are required to ensure minimal bacterial growth; between $10\text{ }^{\circ}\text{C}$ and about $60\text{ }^{\circ}\text{C}$ bacteria will grow in storage facilities. Above $60\text{ }^{\circ}\text{C}$ inactivation of bacteria will occur but also proteins and enzymes will be denatured.

Milk is stored in tanks of different capacities, these can be any size (up to 500 m^3). If the tanks are placed outdoors they could be insulated if required.

Storage can be classified in three useful categories:

1 At the initial point of the production line

At the end of the season when milk production is lower, the milk is collected from the farm on alternate days or even less often. This will involve holding milk until sufficient milk has been collected to carry out an economical process run. The longer storage time must be considered in the process design because the milk will be older when it is processed. Quality issues may arise if the storage times and the temperature are not controlled carefully.

Milk storage before processing is also required while waiting for routine laboratory tests for bacteria, antibiotics or composition.

2 Storage within the processing operations

Storage is sometimes required as part of the process operation. For example, a buffer tank needs to compensate for temporary stoppages in the production or in the packing line. Also storage is required when processes do not overlap because of different processing capacities.

3 At the end of the production line

Some products for the export market have to be stored until the shipping volume has been reached. At this stage the product is normally in a suitable form to enable it to be stored easily without microbiological problems.

Limitation in storage times

During the storage, the fat and protein in milk may undergo chemical changes in three ways. The first two are oxidation and lipolysis that degrade the flavours, principally in milk and butter (Bylund, 1995). Another chemical change is age thickening where the viscosity of milk concentrates increases as they are held (Winchester, 2000). Therefore, storage times should be minimised.

4.7 Packaging

Food preservation relies on the process operations designed to stabilise the food material against food degradation. Influences such as micro-organism spoilage, interaction with components in the environment such as oxygen, gain and loss of water, and protection from high or low temperatures cause food quality loss.

In addition, selecting appropriate packaging operations with the preservation and manufacturing systems are integral components of food process engineering in modern food distribution and marketing (Tung & Britt, 1995). Only those packaging materials

that are hygienically satisfactory can be used for milk and dairy products. Returnable packages, e.g. glass containers, can be reused if they can be cleaned adequately (Kessler, 1981).

The most basic function of packaging is to preserve and protect the product. From a design point of view, packaging is the protection of the quality in the forms of physical, mechanical and microbiological protection from contaminants, for the purpose of safe consumption and intended shelf life use of the product.

The objectives of packaging are the portioning of the products into units that are easy to handle during storage, transport, and consumption, guaranteeing a certain amount of product, and transferring information about the product and its origin (Walstra *et al.*, 1999).

Fresh products, like butter (especially), cheese, frozen cream, ice cream, must be packed as quickly as possible to avoid breakdown of the structure or contamination by the ambient air. Newly packed butter needs cold storage facilities to maintain the temperature below 5 °C (Bylund, 1995; Wilbey, 1986).

Butter is coated on the product side with wax paper or plastic, since oxidation is the main cause of spoilage. The packing material must be impermeable to odours, since butter easily takes foreign odours (Kessler, 1981). Many packing materials are used in the retail market, such as boxes made of wood, cardboard or plastic, as well as metal cans.

4.7.1 Product Characteristics on Packaging

It is very important to study the characteristics of the products because they will have a fundamental impact on packaging. There are varieties of packaging materials such as glass, plastic coated aluminium foil, cellulose, polythene, and polyester. Only packaging materials which are hygienically satisfactory, non-toxic and chemically inert with the product can be used for milk and dairy products.

Secure packaging for milk powder is essential as virtually all dried dairy products are hygroscopic and will absorb moisture quickly if the bag is improperly sealed. The high protein content also requires attention to storage temperature, humidity, and light, because when protein is exposed to light it destroys some essential vitamins and the amino acid methionine (milk protein component) is degraded to methional giving a particular off-flavour called sunlight flavour. Therefore, opaque packages such as plastic and paperboard give good protection under normal conditions (Bylund, 1995).

Fat based products must be protected from light and oxygen to prevent oxidation. Dried whole milk product packaging must be impermeable to water, light and oxygen in order to prevent the oxidative changes or rancidity. Anhydrous milk fat (AMF), and whole milk powders are often packed in an atmosphere of inert gases e.g., N₂, CO₂ or a mixture. The residual oxygen content should be less than 3% (Kessler, 1981).

UHT products require sterile packaging and packing equipment. All post-process handling of products must be within the sterile environment (Bylund, 1995). There are several different package forms used in aseptic processing: cans, paperboard, plastic, foil, plastic laminates, flexible pouches, thermoformed plastic containers, flow moulded containers, and bag in box (Spreer, 1998). There are also wide ranges of hand held containers called bulk totes. These totes are in many styles and options such as attached or detached lids, stack only, nest only or stack and nest to suit the application.

Dried milk products are generally packed when the moisture content is less than about 4% to ensure a satisfactory shelf life (Kessler, 1981). Dried products which are rich in fat should be packaged in materials that are impermeable to light and oxygen to prevent oxidative changes.

Plastics have expanded the packaging industry to very sophisticated levels because of many positive features within their range of versatile properties. Plastic containers are lightweight, which reduces transportation costs, transparent and flexible to almost any requirement, squeezable and moldable in complex shapes, easily coloured and printed, sterilizable, reusable and recyclable. In addition, plastics are economically competitive

in cost with paper, wood, glass, steel and aluminium (Hernandez, 1997). Non-returnable plastics bottles for liquid milk, UHT milk, cream and ice cream have been introduced for packaging operations.

4.8 Other Emerging Processes for Pathogen Control

There are many other emerging processes to be considered in chemical engineering. These emerging technologies are generating much interest in the food industry. The growing demand for safe “fresh products”, if possible with longer shelf life, is influencing the development of industries that process the food products. These new processes tend to use non-thermal preservation treatments.

Emerging processes for pathogen control that may be suitable for the dairy industry include high hydrostatic pressure, ultraviolet light, electromagnetic radiation, electron and gamma rays, ultrasounds and the application of chemical and biological agents such as carbon dioxide (Juriaanse, 1999; Geciova *et al.*, 2002). These are not discussed any further than mentioned below, in this study.

4.8.1 High Pressure

One non-thermal technique that has particular potential is high hydrostatic pressure. An advantage of this new technology is that food quality such as flavours and vitamins are unaffected or only minimally altered. High pressure with temperature and time can be applied for treatment of fresh cheese to inactivate or reduce pathogenic and spoilage micro-organisms and so to increase its shelf life and maintain its organoleptic acceptance. (Trujillo *et al.*, 2002). High pressure affects not just the microbiology of food, but also the chemical and physical properties. For example, whey protein has poor foaming properties, but high pressure treatment of β -lactoglobulin in whey improves the foaming properties by making it far more surface active and improving foam stability (Buchanan & Paterson, 2002). This could have application in, for example, making cappuccino coffee, where milk which foams would be considered desirable.

A practical application of high pressure is for the acceleration of cheese ripening because the cheese storage for ripening can be expensive (Trujillo *et al.*, 2000; Trujillo, 2002; Buchanan & Paterson, 2002). It is also claimed that thicker, or creamier yoghurts can be made with high pressure-treated milk (Buchanan & Paterson, 2002).

High pressure application on milk and dairy products has recently increased (Geciova *et al.*, 2002). Pressures between 300 and 600 MPa have been shown to be a promising effective method in dairy products.

4.8.2 Ultraviolet Light

The use of ultraviolet light for water sterilisation has the advantage that it introduces no additional materials and does not change the chemical composition of the fluid. However the process has not been used widely because of the operation and maintenance problems linked to quartz tubes which separate the source from the water. Ultraviolet Technology Inc. (UTI) claims to have overcome this problem by using fluorocarbon tubes to contain the water during sterilisation. The fluorocarbon tubes are chemically inert, non-wetting, and resistant to fouling. Some commercial installations have been in continuous operation on turbid seawater for over three years without any need for cleaning (Cruver & Jhavar, 1980; Howell, 1990).

Ultraviolet rays do not penetrate deeply into the irradiated body and will be only suitable for the irradiation of premises (e.g. in cheese ripening rooms), and surface irradiation of hard cheese, for sterilising air and water in relatively thin films, tanks and other equipment (Kessler, 1981). Ultraviolet light is also used for sterilisation of medical and biomedical products (Hernandez, 1997).

4.8.3 Electromagnetic Radiation

Energy in the form of electromagnetic radiation at microwave frequencies is coupled directly to food so that energy absorption and hence heating take place throughout the food. Therefore, conduction is not the primary mode of heating and the heating rate becomes more rapid (Sharma *et al.*, 2000).

When these high-frequency electric fields are applied to foods, the electric dipoles of water molecules are excited into rapid oscillation and some of this energy is converted into heat. The practical efficiency of the microwave heating depends on the depth to which the microwaves penetrate into the material. Commercial microwave heating uses frequencies in the region of 900 MHz. However, for safety reasons domestic microwaves use 2450 MHz at which the penetration depth is low (commonly in the order of 10 mm) but, which can lead to overheating at the surface (Sieber *et al.*, 1996). Thicker food products will still rely on conduction to complete the heating process. Therefore, the geometry of the products is an important consideration in designing microwavable foods (Sharma *et al.*, 2000). Domestic microwaves do not give safe and uniform heating of the total product (Sieber *et al.*, 1996). For example, microbial contamination that needs to be destroyed by 30 minutes in the oven may survive reheating in the microwave (Fryer, 1997).

4.8.4 Electron and Gamma Rays

Electron beams and gamma rays have an ionizing effect. Studies on the inactivation of micro-organisms showed that doses of electron and gamma rays reduce micro-organisms (Ito & Islam, 1994). The more ions are produced per unit distance travelled, the greater is the density of ionisation. But, the loss in energy that occurs increases correspondingly and the depth of penetration of the radiation decreases (Kessler, 1981).

Gamma rays possess a lower ionisation density and therefore have a deeper penetration than the electron beam radiation, which has a high ionisation density (Kessler, 1981). Table 4-5 shows that electron beams are more suitable for flat thin pathways.

Table 4-5 Penetration of γ -rays and electron beams in water (Kessler, 1981)

Radiation	Energy in MeV	Penetration (cm)
C _o - 60	1.1 and 1.3 γ	~ 10
C _s - 137	0.66 γ	~ 7.5
electrons	1	~ 0.5
electrons	3	~ 1.5

γ = Penetration of gamma rays and electron beams in water.

These processes are not yet widely applied. Their main disadvantages are their low inactivation effect, high costs and legal barriers (Spreer, 1998). In addition, consumer acceptance of any form of radiation is often low.

4.9 Mass Balances in Dairy Processes

Mass balances for a process design are very important because they can be used to determine the process stream flows and compositions. There are three types of mass balances used in this research. The first is the initial approximate mass balance that is required in the initial process design to aid the overall flow evaluation from the feed to a final product flowsheeting calculation. The second is the component mass balance to calculate the enrichment or depletion of the milk components according to the feed and product specifications. The third is the mass balances around an individual process operation.

The overall mass balance is very often determined by the inlet flowrate of milk, which because of seasonal variation, cannot always be controlled. Generally the design must be based on the peak supply of milk.

A mass balance for the annual production of products needs to be based on the sum of predicted daily flows. In New Zealand a rule-of-thumb states that the annual production equals 185 days production at the peak daily supply.

The exact composition of raw milk does not need to be known as it varies during the year and from farm to farm. A typical value and a range are more useful. If the design calculations are well laid out on a spreadsheet, the impact of variations can be easily determined.

There are losses from each process arising from flushing at start up and shut down and from accumulation of product within the process. They are typically average 1% to 2% of the total feed flows.

Morison (1997a, 1997b) has defined mass balance for some milk process separations in terms of input and output streams of milk components. The following mass balances are based on those systems of equations also published by Morison. A system of equations can be defined for the dairy process product as shown in the following equations:

Nomenclature

F_j	Flow rate of stream j [kg hr^{-1}]
$x_{j,i}$	Mass fraction of component i in stream j
n	Number of components
m	Number of streams

1. The overall mass balance

$$\sum F_{in} = \sum F_{out} \quad (4-10)$$

2. The component mass balances in an aqueous system

$$x_{j,n} = 1 - \sum_{i=1, n-1} x_{j,i} \quad \text{for each stream } j = 1, m \quad (4-11)$$

3. The component mass balance over the process for each component

$$\sum_{j=1, m_{in}} x_{j,i} F_{in,j} = \sum_{j=1, m_{out}} x_{j,i} F_{out,j} \quad i = 1, n-1 \quad (4-12)$$

4.9.1 Guide to Mass Balance Rules

The mass balance rules can be developed by considering the functions of the process units, and by making use of any constraints on the stream flows and compositions that arise from consideration of product specification, product safety and equipment design limitations.

To obtain mass balances in dairy processes some specialised knowledge and relationships need to be used.

Order of calculation

1. Find the limiting milk component by:

Given feed flow of components and the product composition, find which components can have zero depletion while separating others out. For example, for production of cottage cheese, casein is a limiting component.

Hence find the maximum product flowrate.

2. From the product specification and product flowrate, calculate the feed composition required.

Add in knowledge (Morison, 2003 personal communication) of process yields as given in Section 4.9.3.

3. Add processing constraints imposed by the process or equipment.

4.9.2 Mass Balance Guidelines for Different Unit Operations

Suggested techniques for obtaining mass balances within some of the more common unit operations are given below.

Microfiltration, Ultrafiltration and Nanofiltration

The following flow rate balance and solute balance can be obtained for a MF, UF and NF process operations.

There are two parameters that characterised a successful membrane process. One is the selectivity of the chosen membrane and the other is the flow through the membrane (Mulder, 1996), these are described below.

1. The selectivity of a chosen membrane is the amount of solute retain by the membrane, this is called also retention and is defined by the retention coefficient R .

The retention by a membrane affects the fraction of each component that passes through it. The retention coefficient determines the composition of the permeate after microfiltration, ultrafiltration or nanofiltration.

The retention coefficient is given by

$$R_i = 1 - \frac{C_{P,i}}{C_{R,i}} \quad (4-13)$$

Where:

R_i = Retention or sieving coefficient of component i , it is a dimensionless parameter.

$C_{P,i}$ = Concentration of the component i in the permeate [kg/kg].

$C_{R,i}$ = Concentration of the component i in the retentate [kg/kg].

The value of R varies between 1.0 (complete retention of the solute, ideal) and 0 (solute and solvent pass through of the membrane freely).

Typical ultrafiltration retention coefficients for whey are protein 0.99, lactose 0.12, non-protein nitrogen (NPN) 0.08 and fat 1 (Winchester, 1996).

Particles greater than the pore size are usually completely retained by microfiltration so except of loss of fine particles (fines) the yield of the solid particles is close to 100%. Small particles are not retained (0%).

2. Permeate flux is the volumetric (mass or molar) flowrate of fluid passing through the membrane per unit of area of membrane and per unit of time see Section 4.2.1.2.

$$J = \frac{F_p}{A} \quad (4-14)$$

J = permeate flux through a membrane [L/m² hr]

F_p = permeate flow rate through a membrane [L/hr]

A = surface area of contact of membrane and solution [m²]

Reverse osmosis

Only water passes through the membrane. So the retention coefficient is practically 1.0. However, some leakage of small components can occur.

Electrodialysis, dialysis and ion exchange

Detailed knowledge is required of component separation for a mass balance. For example, the ion binding characteristics are required.

Homogenisation

There is no change in composition.

Evaporation, spray drier, roller drier, fluidised bed drier and freeze drier

There is only water removal.

Screen filtration

In screen filtration liquid phase composition is unchanged and the solid material is 100% retained.

Centrifugal Separation

When centrifugal separation is used for fat removal from milk the minimum amount of minimum milk fat in the skim milk is in the range of 0.04% to 0.10%. The amount of fat in the skim milk depends on the fat globule size distribution, and the milk temperature (Morison, 1997a). The maximum fat fraction from a centrifugal separation when fed with whole milk is about 42%. Higher fat fractions can be obtained only if the fat fraction in the skim milk rises about the minimum.

Some separations have a “desludge” to remove solid material from the separator bowl. The effect of this on the mass balance can be assumed to be negligible.

Crystallisation and Precipitation

Generally crystallisation gives a crystal with very high purity but the purifying fat crystallisation from a melt depends on processing conditions.

Precipitation of casein usually forms a curd containing about 90% of the fat but very little of the lactose, whey protein or soluble minerals.

Packaging and storage

There is no change in composition

4.9.3 Mass Balance Rules for Different Products

The mass balance must also reflect actual product recoveries at each step of the process and sensible estimates of inevitable products losses must therefore be made. Suggested guidelines for obtaining mass balances within some of the more common products are given below.

Casein has 99% retention. 1% is lost as fines from separation.

Cheese has 95% casein retention and 5% fines and glycomacropeptide (GMP) solubilised are lost. Cheese has 90% fat retention and 10% goes into whey.

Milk powder has less than 2% losses mostly in cleaning, filtration and others.

Whey protein concentrate has 2% losses and retention losses through membrane .

Butter has less than 0.4% losses in the CIP.

AMF has 0.4% fat losses into butter milk.

Lactose. Lactose crystallisation yield depends from the previous process. For example, some lactose is retained with whey permeate concentrate (WPC).

Minerals separation depends on upstream processes. For example, the pH during separation.

4.10 Economic Analysis in Dairy Processes

Preparation of an accurate mass balance is essential for an assessment of economic viability. For this, the composition of feed and the final product must be known.

Economics are clearly important to be able to make realistic estimates of the process economics during the design and development stages; it is used in determining the viability of a process or product (Pyle, 1997). In this methodology a rough economic estimate needs to be calculated initially when the product is chosen. After that it can be recalculated whenever the designer considers making an alternative choice.

If a process is to be assessed for its viability during the conceptual design phase it will be necessary to estimate the capital and operating costs. Capital cost will depend on the detail design and configuration of the equipment. Detailed estimation is highly specialised job (Pyle, 1997). Operating cost depends on the mass and energy balances, which gives unit costs. They will also include other costs such as labour and it may be necessary to estimate the selling prices for any product and co-product.

When selecting the key process or adding a process to the flowsheet, the economics of the process must be checked. The procedures of estimating capital costs can be found in Gerrard (2000), Jebson & Fincham (1994) and Peters & Timmerhaus (1981). If the process is grossly uneconomic it will be rejected but to allow innovation marginally uneconomic processes will be retained.

5 Dairy Industry Processes from a Product Point of View

5.1 Dairy Products

Prior to developing a conceptual design framework, it is necessary to consider the products that are most commonly encountered in modern dairy manufacturing operations. This chapter reviews the typical production methods for selected product types, examining the key aspects, the constraints and limitations for the design. This will help the designer to conceptualise the development of schematic flowsheet in each case. The key aspects, constraints and limitations that are reviewed will affect the flowsheet design and integration of the process.

This chapter intends to serve as a reference for different product processes in the dairy industry from the design point of view. The list of dairy products is almost endless. It has become necessary to study product and processes in the dairy industry. The products have been selected to illustrate their importance in relevant aspects of design. The selection of information focuses on the schematic process flowsheets from the design point of view. During the product processing description some general aspects are recalled to provide the designer with a basis of understanding of what happens during processing dairy products from the raw milk feed to the packaging. Some general aspects of processing are also discussed. Some other aspects are presented to the extent necessary for understanding the technology.

The development of a range of products is important for diversifying the branded products that help to insulate the dairy industry from the fluctuations of international dairy commodity prices and thereby provide a more attractive environment for long-term investment in the industry.

Main product groups in the dairy industry

The principle products of the dairy industry can be grouped in a number of ways. The following classification is used in this thesis:

1. Liquid milk (Section 5.2)
2. Fermented liquid milk product (Section 5.3)
 - Yoghurt
 - Sour cream.
3. Fat-based products (Section 5.4)
 - Butter
 - Milk-fat based spreads
 - Anhydrous milk fat (AMF)
 - Fractionated fats
 - Phospholipids fat fraction
 - Spreads with vegetable oil.
4. Milk powders (Section 5.5)
 - Skim milk powder
 - Whole milk powder
 - Butter milk powder
 - Milk protein concentrate (MPC)
 - Specialty powders.
5. Casein Products (Section 5.6)
 - Acid casein
 - Rennet casein
 - Caseinates
 - β -Casein fractions
 - Co-precipitates.
6. Cheese Products (Section 5.7)
 - Dry-salted

- Brine-salted
- Specialty cheeses.

7. Whey products (Section 5.8)

- Whey powder
- Whey protein concentrate
- Whey protein isolate
- α -Lactalbumin
- Lactoferrin
- Whey cheese
- Whey hydrolysates
- Whey protein fractions.

8. Lactose Products (Section 5.9)

- Ethanol
- Hydrolysed lactose
- Lactic acid.

The manufacture of all products is subjected to regulations to ensure product safety using good hygienic practices and Hazards Analysis Critical Control Point (HACCP) systems. These systems were established by the food industry to produce safe products through anticipation and prevention of problems (Chandan, 1997; Ramírez-Vela & Martín-Fernández, 2003). Such requirements have considerable impact on the processing operations and production methods. Most regulations require that pasteurisation be used as a pathogen control step in the production of nearly all dairy products. In this thesis, no assumption is made that pasteurisation is the only method of achieving pathogen control. Details of typical pathogen control methods are presented in each product category.

A classification of the principal components of milk with approximate percentages of contents is given in Table 5-1.

Table 5-1 Components of milk (Walstra & Jenness, 1984).

Component	Typical mass fraction %	Range %
Fat	3.9	2.4-5.5
Casein protein	2.6	1.7-3.5
Whey protein	0.65	0.6-0.9
Lactose	4.6	3.8-5.3
Minerals	0.65	0.53-0.80
Water	87.3	85.5-88.7
Miscellaneous	0.3	---

5.2 Production of Liquid Milk

Liquid milk is typically a consumer item but may be used as an ingredient in some baking products. The majority of the liquid milk types have a limited shelf life of only a few days (up to about ten days in New Zealand) and are designed for the local consumer market. The exception is ultra heat treated (UHT) milk, which has extremely low microbiological content and is often called commercially sterile. It may contain thermophilic spores and has a shelf life of several months (up to about nine months in New Zealand).

Liquid milk can be classified in different ways, for example:

a) By fat content:

- Whole milk with natural fat content of 3.5% to 4.5%
- Mixed milk or standardised milk with fat content of 1.0% to 3.5%
- Skim milk or fat-free milk with a fat content of < 0.05% to 1.0%
- Cream with a fat content of about 41% and related liquid products.

b) By heat treatment methods:

- Pasteurised milk
- Ultra heat treated milk (sterilised milk)
- Can sterilised milk.

c) By modification of the composition of the milk by addition, modification or removal of components:

- Evaporated milk
- Sweetened condensed milk
- Enriched milk, mostly with calcium, vitamin D or protein
- Flavoured milk, i.e. with chocolate, vanilla.

d) By mechanical means process application, disruption of fat globules:

- Homogenised milk.

The customer perception of milk and milk quality has undergone quite a transformation over the past two decades. In recent years there has been considerable diversification of the types of milk available on the market (Varnam & Sutherland, 1994). There is an ever-growing list of liquid milk and cream products in New Zealand. Examples of liquid milk and cream products is shown in Table 5-2, along with approximate fat, protein and total solid (TS) composition.

Table 5-2 New Zealand industrial liquid milk and cream products.

Milk type	Protein	Fat	TS	Process operations			
	%	%	%	Standardisation	Pasteurisation	Homogenisation	Enriched
Breakfast brown top	3.3	4.8	12.5	(full cream)	✓		
Blue top	3.1	3.3	12.0	fat reduction	✓	✓	
Light blue	3.8	1.5	10.0	fat reduction	✓	✓	
Green top Trim milk	3.9	0.5	10.0	fat reduction	✓	✓	extra 26% calcium
Green top Super trim	4.4	0.1	10.0	fat reduction	✓		
Silver top	3.1	3.8	12.0	fat reduction	✓		
Yellow top Calci extra	5.6	0.1	10.0	fat reduction & UF retentate	✓		extra 74% calcium
Flavoured	3.2	1.5	10.0	fat reduction	✓	✓	flavours
Cream	4	35	40.0	fat enrichment	✓		
Evaporated	14	8.3	34.0	dry matter content	✓	✓	to 23% SNF,
Sweetened Condensed	28	8.3	70.0	dry matter content	✓	✓	Addition of sucrose 42.7%

5.2.1 Liquid Milk Process

There is generally little difference between the different liquid milk types. The simplified diagram presented in Figure 5-1 shows a schematic representation of the liquid milk process, with the fundamental process operations from a design point of view.

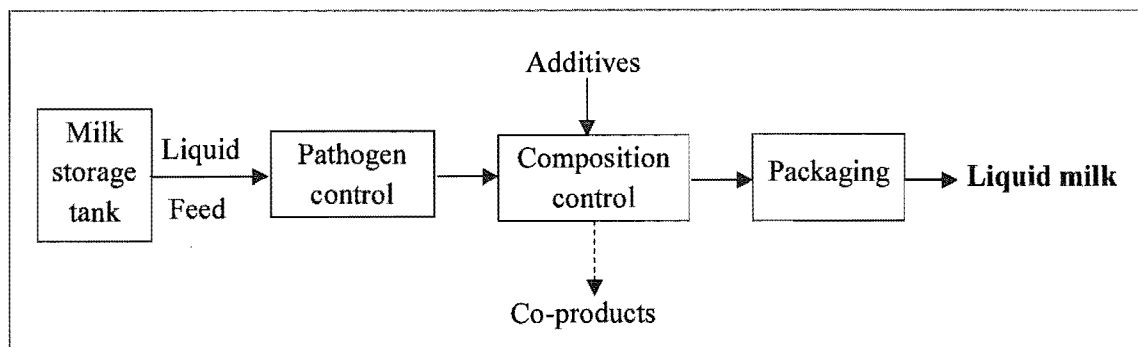


Figure 5-1 Schematic flowsheet of liquid milk production.

The production of liquid milk originally was part of the home farm economy. Gradually, it became a different operation in small-scale local production and later in large industrial production.

1. Small-scale local production

In some less mechanised or developed agricultural systems, such as those found in the Andes, milk is purchased directly from the farmer and is heated to its boiling point as a means of pathogen control. In quantities of twenty litres to 5000 litres per day, this milk can be sold directly to households in accordance with the number of family members.

This type of delivery system is limited by the size of the farm and the population in the vicinity. In the developing countries, milk is consumed generally as whole milk or naturally skimmed milk and the cream is used directly as spreading cream.

2. Large industrial scale production

The need for milk to be kept at a temperature lower than 6 °C has prompted dairy factories to set up and maintain a farm-gate to home refrigerator chill chain (Spreer, 1998). In New Zealand, the aim is to keep the milk below 4 °C after pasteurisation.

Milk processed in an industrial scale operation is heat treated (Section 4.1.4) to destroy the harmful bacteria before it can be commercially distributed. The centrifugal clarification based process of bacto-fugation (Section 4.2.2) and microfiltration based bactocatch (Section 4.2.1.2) are used also to control pathogens.

To meet the demand for a liquid milk that is stable for extended periods at room temperature, ultra heat treated milk was developed (UHT), where the milk is subjected to much stricter microbial limits. Aseptic packaging is a critical control point for UHT, as described in Section 4.7.

The composition of raw milk is not constant during the season. Some form of composition control (“standardisation”) is required to keep the product consistent from one batch to the next. In addition, because of the market demands, many of the products have compositions standardised to customer preferences. Typically, the fat content is reduced. Composition control includes centrifugal separation (Section 4.2.2) to separate cream from skim milk, ultrafiltration (Section 4.2.1.2) to produce protein enriched and protein depleted streams, recombination of any separated streams, and the addition of flavours or vitamins depending on the product type.

Homogenisation (Section 4.4) can be loosely considered as a composition control process as it changes the fat globule size, prevents the “creaming” in milk and thus gives better keeping qualities. Homogenisation is a requirement for UHT with its longer shelf life (Spreer, 1998).

5.2.2 Production Requirement and Constraints

Other than the requirements mentioned above, or those required by regulation, there are no specific constraints.

On a small scale, there are few co-requisites because the production is simple, does not require many utilities and does not produce co-products.

Large-scale production typically requires an energy source of at least 80 °C and electricity. Unless the market is perfectly balanced, there is likely to be a need for a process to take excess cream. A local butter or AMF factory would fill this need.

5.3 Production of Fermented Liquid Milk Products

In locations with high quality milking and good milk collection, distribution and transportation facility systems, the need for fermentation as a preservation method does not exist unless there is a customer demand for fresh fermented milk products. However, in regions where such facilities are lacking, the fermentation of milk as a means of preservation has kept its original importance. Lactic acid bacteria alter the composition of the milk in such a way that most undesirable organisms and pathogens cannot grow or even die. These conditions include pH (4.6 to 4.0) that helps in maintaining a low pH in the stomach after consuming the fermented product (Walstra *et al.*, 1999). Fermentation is a fairly simple, cheap and safe way to preserve milk.

Milk products produced by lactic acid fermentation are known as yoghurt, kefir, sour cream, cultured buttermilk and acidophilus milk. They are called also fermented or cultured milk. The milk for these products is mixed with a starter culture, which converts part of the lactose to lactic acid and carbon dioxide. Acetic acid, diacetyl, acetaldehyde and several other substances are also formed in the conversion process. These give the products their characteristic fresh taste and aroma (Bylund, 1995).

5.3.1 Yoghurt Process

This is one of the most popular fermented fresh dairy products. Yoghurt is a firm, creamy or liquid acidified milk product that is manufactured from standardised, pasteurised and homogenised milk using starter lactic acid bacteria (Spreer, 1998). It is made in a variety of compositions of fat and dry matter content (Walstra *et al.*, 1999). An increase in the total dry matter content, particularly the proportion of casein and whey protein, will produce a firmer yoghurt coagulum and the tendency of whey separation will be reduced (Bylund, 1995). Yoghurt's popularity is promoted by the use of fruit and various flavours (e.g., vanilla, honey, coffee, essences) and aroma additives, especially fruits and berries in syrup. Table 5.3 shows a typical fruit yoghurt composition.

Table 5-3 Typical fruit yoghurt composition (Bylund, 1995).

Component	w/w %
Fat	0.5 – 3.0
Lactose	3.0 – 4.5
Milk solids non fat (MSNF)	11.0 – 13.0
Stabiliser (if used)	0.3 – 0.5
Fruit	12.0 – 18.0

Production of Yoghurt

The milk is clarified, and separated into cream and skim milk, and then standardised for composition control to achieve the desired fat content. It is pasteurised to produce a relatively sterile product. To enhance the viscosity and texture of the yoghurt, the milk is homogenised at a temperature of about 65 °C and at a pressure of about 200 bar (Varnam & Sutherland, 1994; Kessler, 1981). Homogenisation of milk prevents creaming of the fat during the incubation period, ensures a uniform distribution of the milk fat, stabilizers and other added ingredients, and increases the stability to the yoghurt (Varnam & Sutherland, 1994). The milk is brought to the incubation temperature and the yoghurt culture (consisting of acid lactic bacteria) is added to it (Kessler, 1981). The starter culture produce lactic acid that lowers the pH and coagulates the casein proteins. The gel (coagulum) is formed at this stage. After that, it is cooled to a temperature of 38 °C to 45 °C (the optimum growth in the culture). During gel formation, the milk must remain stationary (see Figure 5-2). The pH is monitored until it has reached 4.4 to 4.6 and at this time, it is cooled and fruit or flavour is added and the product is stored at refrigerator temperature (Bylund, 1995; Walstra *et al.*, 1999).

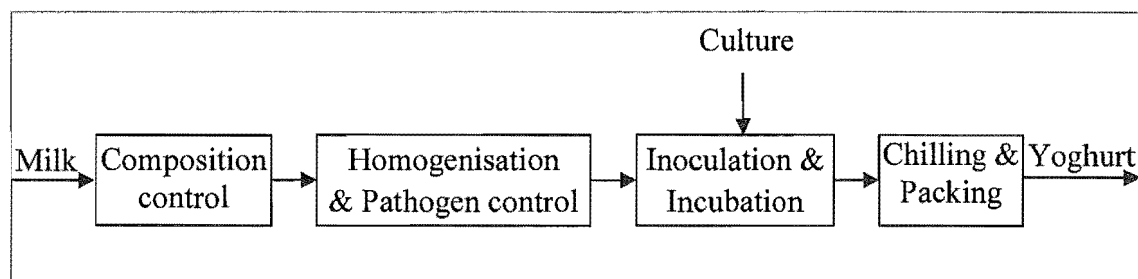


Figure 5-2 Schematic flowsheet of yoghurt production.

Yoghurt has a short shelf life at temperatures over 10 °C, and lasts for only for 2 to 3 weeks at a refrigerator temperature without a significant loss of quality (Kessler, 1981), which makes it a product suitable only for local markets.

In order to extend the shelf life of the yoghurt the plant can be run in an aseptic mode and the process requires hygienic installation and filling facilities (Bylund, 1995; Spreer, 1998).

The nutritional value of yoghurt is also enhanced by raising the non-fat solids content by the addition of milk powder, evaporation under vacuum or water removal by ultrafiltration membrane (Robinson & Tamime, 1986). The air content of the milk used to make cultured milk products should be as low as possible because dispersed air causes incrustation on heating surfaces (e.g., in pasteurisers) and reduction of the stability of the yoghurt (i.e., expulsion of whey). If incoming air is unavoidable e.g., when adding milk powder, then deaeration (see Section 4.2.2) should be included as part of the process (Bylund, 1995; Spreer, 1998).

5.3.2 Sour Cream Process

Sour cream is also known as a cultured cream. It is a fermented milk product manufactured using *Streptococcus lactic* subspecies as the starter cultures. Sour cream, like other cultured products, has a limited shelf life. Sour cream is HTST pasteurised (see Section 4.1.4 on Table 4-1 cream pasteurisation). In the event of extended storage, enzymes from the lactic-acid bacteria (which break down the β -lactoglobulin) become active and the sour cream becomes bitter. It also loses its flavour due to the diffusion of carbon dioxide and other aromatic substances through the packaging (Bylund, 1995).

Production of Sour Cream

The fat content of the cream is standardised to between 12% to 30% depending on the required properties of the final product. The standardised cream is then heated to 75 °C to 80 °C before the homogenisation takes place at high pressure and temperature more than 130 bar and at to 60 °C to improve the texture (Varnam & Sutherland, 1994), then it is cooled to 20 °C to 25 °C before addition of starter culture. The starter culture is added to between 1-2 %, fermentation proceeding for few hours at 25 °C. The fermentation is stopped when the pH has reached 4.5 pH by cooling and storage at 5 °C

to increase the storage life. The homogenisation is preferably at a low temperature to promote the formation of a homogenisation cluster. Figure 5-3 shows a schematic sour cream flowsheet.

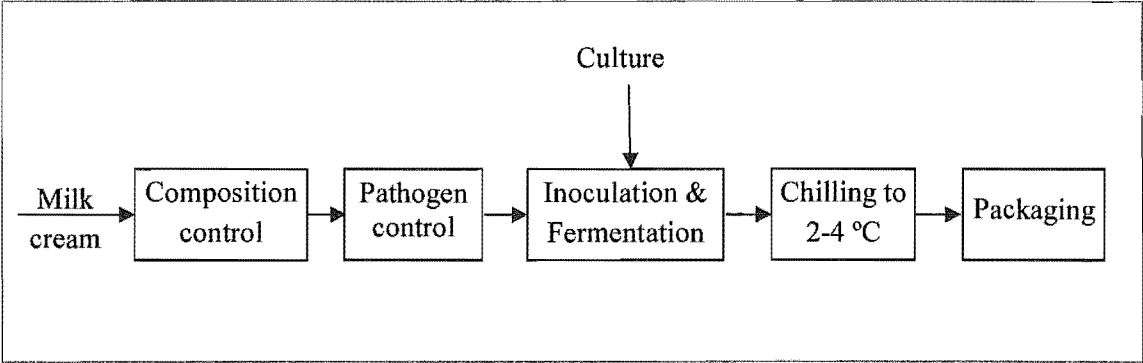


Figure 5-3 Schematic sour cream production flowsheet.

The inoculation and fermentation conditions are similar to those for yoghurt. The fermentation stops at 4.5 pH and then the cream is cooled, gently stirred and packed. The consistency of cultured cream can be adversely affected by post-fermentation handling (Varnam & Sutherland, 1994). Sometimes inoculation and fermentation take place in the final retail pack (Spreer, 1998).

5.3.3 Production Requirements and Constraints

Culture preparation must be done under aseptic conditions in order to avoid contamination and bacteriophage infection (Spreer, 1998; Bylund, 1995). Cultivation of starter culture must be done on an enclosed production line until the culture product is packed.

5.4 Production of Fat-based Products

Milk fat exists as small globules dispersed in the milk serum. Milk fat globules have an inner core, composed of 98% triglycerides, which is surrounded by a lipid membrane composed primarily of phospholipids. The milk fat globule membrane is a layered structure that has an inner layer of high-melting triglycerides, followed by a layer of polypeptides, which are interspersed in a lipid continuum of phospholipids and cholesterol (Kaylegian & Lindsay, 1995). The membrane contains a variety of compounds including phospholipids, lipoproteins, glycerides, cerebroside, copper, iron

cholesterol, trace elements, bound water, vitamins A, D, E and K (Bylund, 1995; Walstra, *et al.*, 1999). Milk fat globules range in diameter from 0.2 µm to 20 µm although small globules (less than 1µm) are the most abundant, but account for only a small percentage of the total lipid (Bylund, 1995; Kaylegian & Lindsay, 1995).

Milk fat can be incorporated into commercial prepared foods through the use of anhydrous milk fat, butter and cream dairy products. The choice of milk fat ingredients usually depends on the need of final application. Typical analyses of these product are presented in Table 5-4.

Table 5-4 Composition of some products containing milk fat (Kaylegian & Lindsay, 1995).

Ingredient	Milk fat (%)	Water (%)	Solids non-fat (%)
Butter	81.1	15.9	3.0
Butter oil	99.3	0.5	0.2
Anhydrous milk fat	99.8	0.1	0.1
Heavy whipping cream	37.0	57.7	5.3
Light whipping cream	30.9	63.5	5.6
Light cream	19.3	73.7	7.0
Half and half	11.5	80.6	7.9
Liquid whole milk	3.3	88.5	8.2
Dried whole milk	26.7	2.5	70.8
Evaporated milk	7.6	74.0	18.4
Sweetened condensed milk	8.7	27.1	64.2

Butter and other milk fat-based products like anhydrous milk fat are important for their nutritional value, they are a source of fat soluble vitamins such as A, B, E, K, for the functional properties such as the flavour and for their rheological properties of dairy products and foods in which they are used (Fox & McSweeney, 1998). While the value of milk fat is less than the milk proteins, it is still significantly more valuable than vegetable oils.

Milk fat product is particularly valued not only due to its desirable flavour, but also because of its influence on a pleasant mouthfeel (McSweeney *et al.*, 1997), and hence its ability to make much of the food palatable (Chandan, 1997). The palatability of the dairy fats is due to the large number of lipids of small molecular size (Varnam & Sutherland, 1994). The major flavour compounds include short chain fatty acids (Chandan, 1997).

The fat content, moisture content and the state of crystallisation of butter affect its texture. Milk fat consists of many different triglycerides that do not form pure crystals but tend to crystallise in groups of similar size and structure. The melting points of pure triglycerides in milk range from -30 °C to 72 °C (Walstra *et al.*, 1999). The presence of mixed crystals means that the melting points of milk fat are different from those of the individual pure triglycerides, giving a reduced overall melting range from -40 °C to 37 °C; the milk fat final melting point is usually about 37 °C (Walstra & Jenness, 1984). One intriguing property of a pure triglyceride is that it has multiple melting points due to three distinct crystal forms (polymorphism); the proportions of each crystal form depend on the method of crystallisation (Spreer, 1998). Thus, both the polymorphic forms and the composition of the mixed crystals influence the butter texture.

Seasonal changes in milk composition may affect the hardness of milk fat. Feed composition can affect the fat content of milk, especially its fat composition (Walstra *et al.*, 1999). Milk fat tends to be softer during the spring months when cattle are fresh pasture fed in some countries; in New Zealand, cows are pasture fed all year around but variations such as state of lactation and weather still affect fat composition.

The minor components (see Table 5-5) are important to the nutrition and function of milk fat. The phospholipids provide the emulsifying properties. β -carotene provides the distinctive yellow colour of milk fat. There are also concentrations of the fat-soluble vitamins such as vitamin A and vitamin E (Fox & McSweeney, 1998).

Table 5-5 Average lipid composition of milk (based on Walstra *et al.*, 1999; Fox & McSeeney, 1998; Varnam & Sutherland, 1994; Waslra & Jenness, 1984).

Lipid	% in milk fat (w/w)
Triacylglycerols	97-98
Diacylglycerols	0.3-0.6
Monoacylglycerols	0.02-0.04
Free fatty acids	0.1-0.4
Free sterols	0.2-1.0
Sterol esters	Trace amounts only
Vitamin E	Trace amounts only
Carotenoids and vitamin A	0.002
Phospholipids	0.2-1.0
Hydrocarbons	Trace amounts only

The fat globules are highly prone to lipolysis unless inactivation by high-temperature pasteurisation of lipases is complete (Varnam & Sutherland, 1994; Bylund, 1995).

The rupture of the milk fat globule membrane in areas of high shear can have a negative influence in milk fats. It makes them susceptible to fat degradation (Spreer, 1998). A variety of physical defects in milk, and especially in cream, are caused by rupture of milk fat globule membranes. For example, oiling off, cream plug and age thickening due to a high level of free fat. Once the milk fat globule membrane has been broken the fat is exposed to the lipase enzymes. Lipase enzymes breakdown fat molecules into glycerol and free fatty acids causing undesirable flavour changes.

5.4.1 Cream Process

All fat-based products involve an initial step of cream separation that is currently done by centrifugal separation (Section 4.2.2) using the difference in densities between the fat globules (930 kg/m^3 at 15.5°C) and the other aqueous components (1030 kg/m^3 at 15.5°C) (known as serum). In normal practice, cream with a fat content of about 41% can be obtained while still achieving good skimming of the milk. Higher fat contents can be achieved by slowing the cream off-take flow. This increases the residence time in the separator, but the skim milk fat content can also become higher.

Cream for consumption as a liquid can be standardised by blending with the skim milk to achieve a range in fat contents. Cream, or the whole milk that it is separated from,

must undergo a pathogen control step, which is nearly always a pasteurisation. Membrane based processes cannot be used because the size of fat globules are similar sizes to those of pathogen organisms. Some regulations require that if cream is transported from one site to another, the pathogen control step must be after transport.

Some traditional creams, such as Devon clotted cream, are produced by gravity separation from a batch, with or without heating.

5.4.2 Butter Process

Butter is made from cream by any process that causes a phase inversion. Cream is an emulsion of fat globules in a continuous aqueous phase (oil-in-water) while butter is an emulsion of droplets of milk serum (water, protein, lactose, and possibly salt) in a continuous phase of semi crystalline milk fat (water-in-oil emulsion).

Butter was originally made on the farm for household use (Farrall, 1952). A manually operated butter churn was used to break the fat globules followed by the discharge of buttermilk until the required moisture content and structure were achieved (Bylund, 1995). Buttermilk is a co-product of butter production from sweet or fermented cream; buttermilk fat content is about 0.5% and it contains higher levels of membrane compounds of fat globules, especially phospholipids.

Butter is mainly a consumer item and contains important fat-soluble vitamins, especially vitamin A (Spreer, 1998). It may be also used as an ingredient, for example, in some baking recipes.

There are two commercial butter making processes used in New Zealand: the Fritz process developed from the traditional churning process of crystallised cream and the Ammix process where fresh milk fat is mixed with cream, skim milk and salt and shock cooled to give rapid crystallisation.

5.4.2.1 Fritz Butter Process

W. Fritz introduced the Fritz butter process technology developed from the traditional cream churning process, in 1940. He developed a continuous butter making process which was later further developed by Eisenreich (Kessler, 1981).

Cream is vacuum-pasteurised, usually at 95 °C or higher, normally without any holding time, and steam-stripped to reduce some of the undesirable flavours (Bylund, 1995). After that, the cream is cooled causing some of the fat to crystallise, thus providing some rigidity to the fat globules for optimum butter making. This is followed by phase inversion that occurs during the churning of cream. Under intense agitation, some of the membranes break, which releases fat that binds other globules. This forms butter granules that are too large to remain in suspension. The fat thus separates and the buttermilk (largely serum) is released and drained off until a stable water-in-fat emulsion is obtained.

The next step is called working (or kneading), that is the process of crushing the remaining fat globules and liberating additional free fat. The emulsion breaks and additional milk fat is freed which becomes part of the continuous phase of the butter released by this process, giving the homogeneous structure that is characteristic of butter. This concentration process raises the fat content of the butter to the final level of between 80% and 84% fat. (Kessler, 1981; Chandan, 1997 & Waslra *et al.*, 1999). Salt may also be added. The final working is under vacuum, which removes air to give a smooth even texture. Packing machines then pack the butter (Section 4.7). Figure 5-4 illustrates the main operations in this butter making process: pathogen control, fat concentration, crystallisation, phase inversion and working to the formation of a stable water-in-oil emulsion.

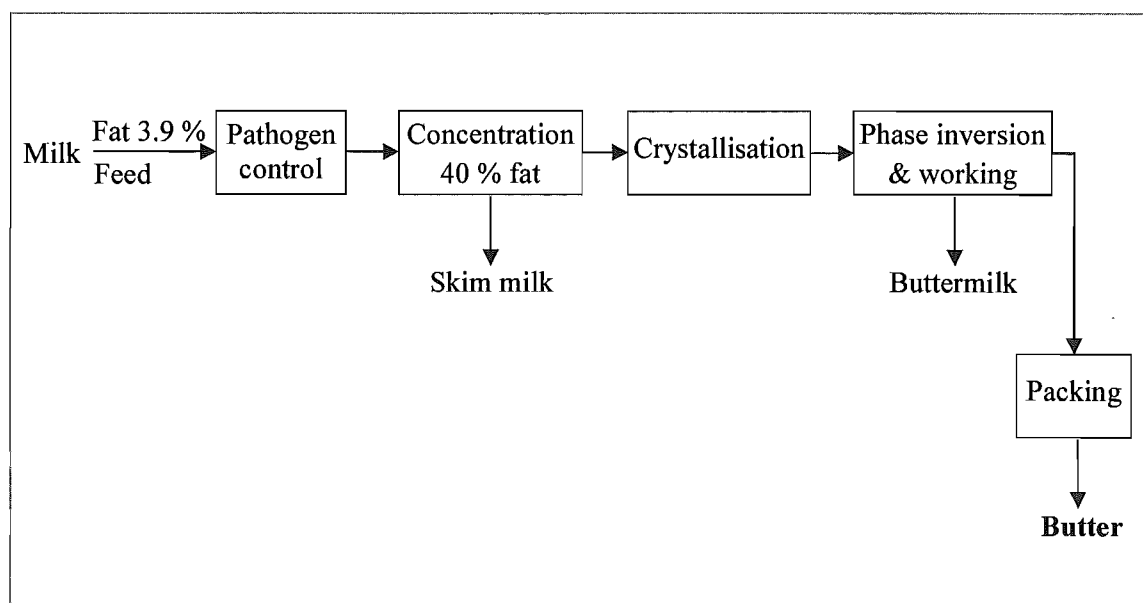


Figure 5-4 Schematic flowsheet of Fritz butter production.

Table 5-6 shows a typical butter composition.

Table 5-6 Typical butter composition (based on Walstra *et al.*, 1999; Chandan, 1997).

Major Components	Salted butter (%)	Unsalted (%)
Milk fat	81.4	82.8
Moisture	15.7	15.7
Non fat milk solids	1.4	1.5
Salt	1.5	0.0

5.4.2.2 Ammix Butter Process

In the Ammix butter process, skim milk, anhydrous milk fat (AMF), cream and salt or flavourings are mixed in appropriate proportions and shock-cooled in a scraped-surface heat exchanger where crystallisation occurs in a matter of minutes, rather than hours as required by the Fritz process (Cant *et al.*, 1998). The semi-solid butter is worked in a “pin worker” to destroy some of the crystal structures to give a softer product. The process is considered to be more flexible than the Fritz process. This process is also called the modern churn (Fox & McSweeney, 1998).

Variations of the Ammix process are used to make a wide range of functional milk fat products that cannot be made by the Fritz process. These include the spreadable butter (which spreads from the refrigerator), tropical butter (which does not oil off at high ambient temperatures), low fat spreads, bakery ingredients such as special butters for pastry and cakes (where the butter needs to remain plastic and fold easily without tearing the laminating steps), vegetable oil blends, including fat mixtures and blended table spreads (Chandan, 1997). Other spreads are described in Section 5.4.6.

Figure 5-5 shows the Ammix butter production flowsheet.

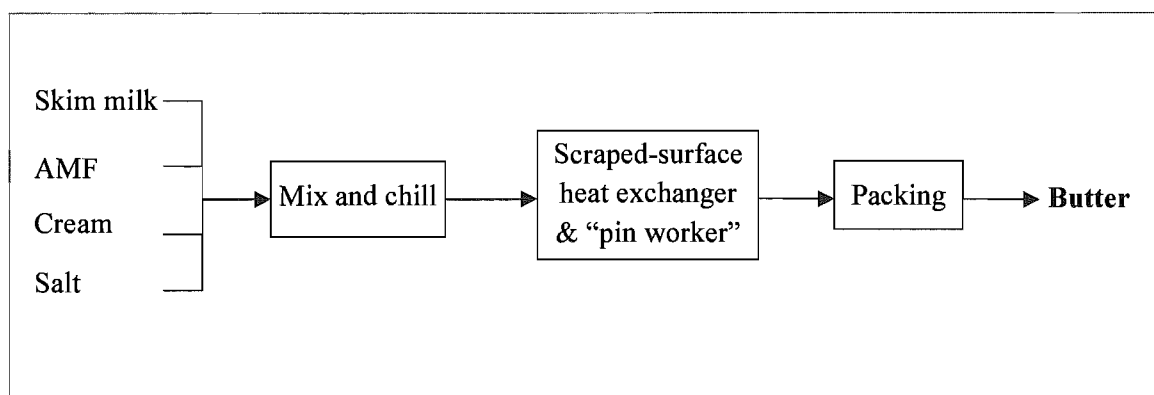


Figure 5-5 Schematic flowsheet of Ammix butter production.

5.4.3 Anhydrous Milk Fat (AMF) Process

Anhydrous milk fat (AMF) was originally produced in Australia during World War II by melting butter and purifying it by subsequent treatment in centrifugal separators (Fjaervoll, 1970; Al-Tahiri, 1987). Jensen and Nielsen (1982) stated that AMF is used as a major source of fat for the recombination of milk and milk products because of its good keeping quality, as it remains edible for months at room temperature (White, 1953; Al-Tahiri, 1987).

Anhydrous milk fat, also called clarified butter, butter oil or ghee, can be stored at temperatures less than 10 °C for several months without deterioration. Anhydrous milk fat should have a minimum fat content of 99.8%; the prefix anhydrous being applied where the moisture content is less than 0.2% (Varnam & Sutherland, 1994). Anhydrous milk fat is excellent for transporting and storage as it requires less space than butter, which used to be the traditional way of storing butterfat (Bylund, 1995).

AMF is not normally consumed directly but is used for cooking and as an ingredient, e.g. in products such as chocolate and pastries. The advantages of using anhydrous milk fat or butter-oil are no splattering or burning during sautéing, increased puff for pastries and pie shells, aroma and flavour enhancement in bakery items, control of fat bloom in chocolate candy and ease of melting, pumping and mixing with other food ingredients (Chandan, 1997). AMF is also recombined with skim milk powder and water to be used as a substitute for fresh fluid milk (Al-Tahiri, 1987), especially in countries with an insufficient supply of fresh milk.

The anhydrous milk fat (AMF) can be processed by two methods (Bylund, 1995). The first method is a continuous flow direct from cream milk as shown in Figure 5.6. The basic process involves the disruption of the milk fat globule membrane in order to break the emulsion, followed by the removal of the solids non-fat (buttermilk) and water phase. This disruption is achieved by centrifugal pre-concentration of the fat to about 75% fat. Then the phase inversion by homogenisation occurs, followed by the centrifugal concentration up to 99.9%. The heavy fractions contains approximately 20% to 30% fat a is recycled to the incoming concentrated cream.

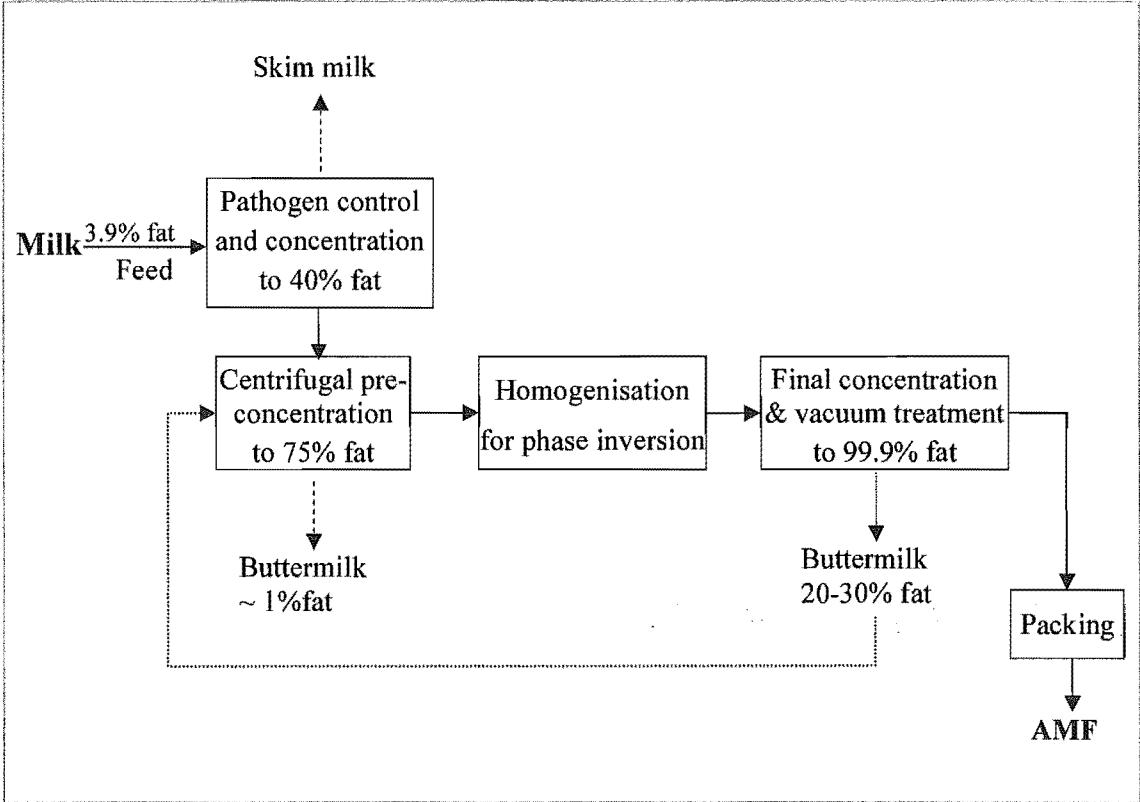


Figure 5-6 Schematic flowsheet of anhydrous milk fat (AMF) production from milk.

The second method of AMF production (Figure 5-7) uses as a raw material off-specification or excess butter, especially butter that is not expected to be consumed within a reasonable period of time.

The melted butter is concentrated in a centrifugal separator. It is then subjected to vacuum expansion until the required 99.5% fat content is reached and this is less than 0.5% water (Kessler, 1981). After this, the light phase containing 99.5% fat can be polished to obtain a clear shiny liquid. It is later neutralised to reduce the number of free fatty acids. This process provides different product types by fractionation where

the oil is separated into high and low melting fats. Each of them has different properties that enable them to be used in a variety of products. Finally, it is packed in the absence of air (see Section 4.7.1).

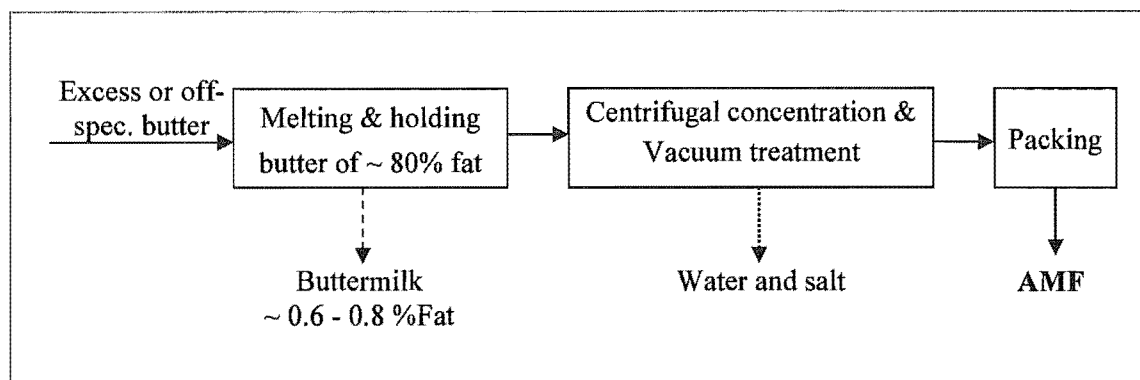


Figure 5-7 Schematic flowsheet of anhydrous milk fat (AMF) production from butter.

5.4.4 Fractionated Milk Fat Process

The most common modification of milk fat is fractionation (Waslra *et al.*, 1999). Fractionation of milk fat to create ingredients with specific functional properties has received considerable attention around the world (Kaylegian & Lindsay, 1995).

The technologies used to fractionate milk fat are crystallisation from melted milk fat, crystallisation from solvent solution, fractionation by short-path distillation and fractionation by supercritical fluid extraction. The most common method for the commercial production of milk fraction is crystallisation from melted milk fat. This method involves a relatively simple physical process and does not employ additives so the product retains its natural image and designation. Milk fat can be separated into different groups of triglycerides with different melting point ranges. A typical process is freeze fractionation from the melt. Anhydrous milk fat is heated to above 40 °C until it is fully molten, and is then cooled slowly to about 29 °C causing the first crystals of the high melting point triglycerides to form. The triglycerides are then separated by dead end filtration (Section 4.2.1) to give a hard fraction and a soft fraction. The crystallisation is slow and by gradual cooling there is more selectivity and the crystals tend to be purer and larger (Bylund, 1995). Fractionation by supercritical fluid (i.e., carbon dioxide) does not employ additives either, but requires a high capital investment, and separates fractions based on molecular weight rather than on melting point. The crystallisation from solvent solution has a concern associated with potential residual

solvent, flavour change, and the hazards and also cost involved with operating a solvent recovery system (Kaylegian & Lindsay, 1995).

Crystallisation of molten fat in an organic solvent (e.g., acetone) provides a means of producing fats and oils with cleaner, sharper defined melting characteristics for use in other applications, but solvent may not be acceptable for use with foods (Fox & McSweeney, 1998).

Over 850 milk fat fractions have been reported in the literature and have been produced by a variety of fractionation methods and processing conditions. These milk fat fractions exhibit a wide range of chemical and physical properties, and consequently they exhibit wide range functionalities (Kaylegian & Lindsay, 1995). Over 600 of the milk fractions have been characterised for melting behaviour. To facilitate the discussion of the functionality of milk fat and milk fat fractions in food products, these melting categories include as follows (Kaylegian & Lindsay, 1995).

- Very high melting milk fat fractions (Melting point > 45 °C)
- High-melting milk fat fractions (Melting point between 35 °C and 45 °C)
- Middle-melting milk fat fractions (Melting point between 25 °C and 35 °C)
- Low-melting milk fat fractions (Melting point between 10 °C and 25 °C)
- Very low melting milk fat fractions (Melting point, less than 10 °C)

Milk fat can also be modified chemically by hydrogenation using H₂ with a catalyst at high temperature, decreasing the number of double bonds and thereby increasing the high melting proportions of a fat. This process is often called hardening (Walstra *et al.*, 1999), but the product can no longer be called milk fat.

Fractionation of milk fat shows potential for the development of novel ingredients with varied functional properties for use in a wide range of food products. Processes such as melt crystallisation and short path distillation are some of the processing that offers a feasible approach to customised fractionation of milk fat.

5.4.5 Phospholipids Fat Fractions Process

Phospholipids are enclosed in the multilayered chemical complex of the fat membrane. They consist mostly of lecithin, which is thought to have a positive effect on the nervous system (Spreer, 1998). Although phospholipids represent less than 1% of total lipids, they play a particular role, being present mainly in the milk fat globule membrane. They represent a considerable proportion of the total lipids of buttermilk and skim milk. Very high level of phospholipids in milk may indicate the presence of mammary cell membranes (Fox & McSweeney, 1998).

Phospholipids have many applications in the pharmaceutical, food, cosmetic and other industries (Ogino *et al.*, 2002).

5.4.6 Spreads with Vegetable Oils Process

The manufacture of vegetable oil spreads is done generally by the Ammix process. Skim milk, anhydrous milk fat (soft and hard fractions), cream and salt, flavourings and vegetable oils are mixed in the appropriate proportions and shock-cooled in a scraped-surface heat exchanger to crystallise (see Figure 5-8). Then, the semi-solid butter is worked in a “pin worker” to destroy some of the crystal structures to give a softer product. Vegetable oils can be added to replace 5% to 25% of the milk fat (Spreer, 1998). The texture and consistency of the spreads is improved by the increased percentage of vegetable oils, which reduces the melting point and leads to a very good spreadability at refrigerator temperatures (Kaylegian & Lindsay, 1995). The commonly used vegetable oils are soy oil, sunflower oil, and olive oil (Spreer, 1998; Walstra *et al.*, 1999).

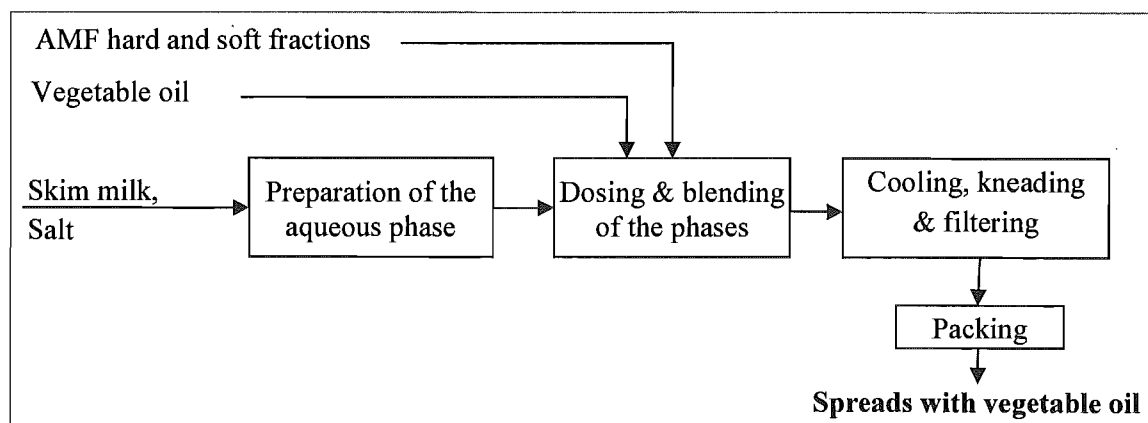


Figure 5-8 Schematic diagram representation of spreads with vegetable oil.

Adding stabilizers and emulsifiers, and increasing the protein content to 5% to 7%, can reduce the total fat content to less than 40%. The raw materials are selected according to the specification of the final product. Blend of milk fat with vegetable oils is mainly used in margarine manufacture. One of the most important concerns in the blending of fats is that the crystallisation properties of the glycerides in the mixture remain compatible. Incompatible glycerides in fats can cause retardation or complete lack of crystallisation (Kaylegian & Lindsay, 1995).

5.4.7 Production Requirements and Constraints

High shear and turbulence should be avoided in the production of fat based products, especially within the pipelines and the pumps. This is because they can cause strong degradation of the membrane and separation of free fat from the fat globules can take place (Spreer, 1998). Furthermore, the free fat is strongly attached to the walls of the containing product. This makes the fat separation more difficult to separate fat during and thus leads to fat losses (Spreer, 1998). Therefore, the mechanical stress when transferring and storing the fat-based products has to be as low as possible.

The fat globule damage may be determined by measuring the level of free fat present (McSweeney *et al.*, 1997). Al-Tahiri (1987) reported that increasing the level of free fatty acids in AMF caused a significant decrease in the acceptability of the recombined milk. Al-Tahiri's results showed that the lipolysed flavour of the recombined milk could be detected by a sharp smell and a strong soapy taste.

Fat-based products are subject to oxidation that causes rancid and oxidised flavours. Nitrogen blanketing can be used to prevent oxidation. The product should be packed in oxygen free conditions using the nitrogen gas in order to have a good stability to fat oxidation such as AMF (Al-Tahiri, 1987). All process steps must minimise the potential of mixing the fat with air, light-induced to reduce lipid oxidation.

5.5 Production of Milk Powders

Milk powder is a long-life product, which can be easily transported, stored and handled as it has a mass and volume about one tenth of the original liquid milk. This product is especially suited to export. It is normally reconstituted to a liquid for consumption but is also commonly used as an ingredient for other foods such as ice cream and chocolate.

Liquid milk contains approximately 87% of water, while skimmed milk, buttermilk and whey contain 91%, 90% and 94% water respectively (Kessler, 1981). The moisture content is nearly always reported on total mass (wet) basis. This section focuses on the production of dried powder products from a liquid feed. Caseinate powder, which could be discussed here, are discussed separately with casein in Section 5.6. The acronyms below will be used in this chapter and Chapter 7.

The most common spray drier powders produced for a variety of uses are:

Skim milk powders	(<i>SMP</i>)
Instant skim milk powders	(<i>ISMP</i>)
Whole milk powders	(<i>WMP</i>)
Agglomerate whole milk powders	(<i>AWMP</i>)
Instant whole milk powders	(<i>IWMP</i>)
Buttermilk powders	(<i>BMP</i>)
Milk protein concentrates	(<i>MPC</i>)
Whey powders	(<i>WP</i>)
Whey protein concentrates	(<i>WPC</i>)
Caseinate powders	(<i>CSTP</i>)
Cheese powders	(<i>CHP</i>)
Cream powders	(<i>CRMP</i>)
Lactose powders	(<i>LACP</i>)

5.5.1 Milk Powder Process

Milk powder processing is essentially identical regardless of the product type. This can be generalised into four main stages: pathogen and composition control (milk treatment), water removal, powder handling, and packing, as shown in Figure 5-9.

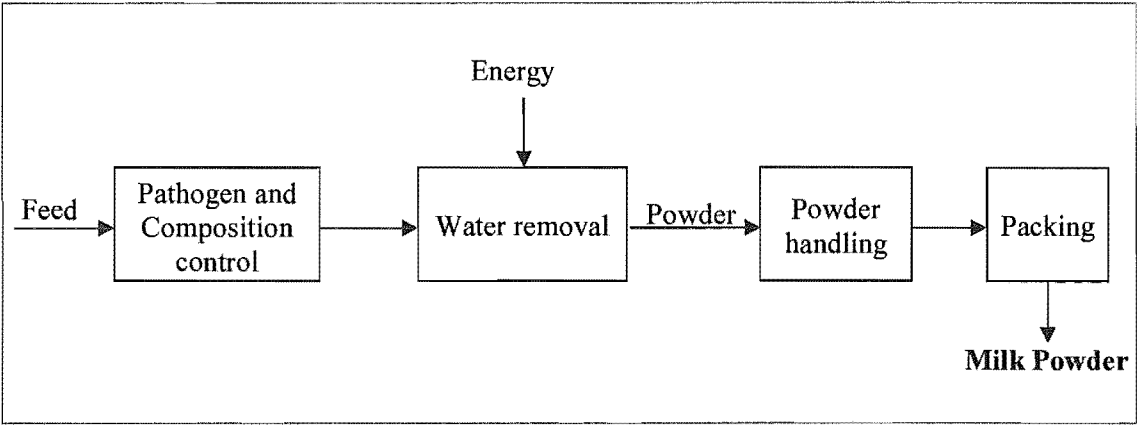


Figure 5-9 Generalised schematic flowsheet of powder production.

Typically evaporation and spray drying are used for the water removing step giving the process shown in Figure 5-10. The most common form of evaporator now used in the New Zealand dairy industry is the multiple effect falling film evaporator, either with thermal vapour recompression (TVR) or mechanical vapour recompression (MVR) (see Section 4.2.3). Other water removal steps such as reverse osmosis (described in Section 4.2.1) are also feasible to remove part of the moisture content.

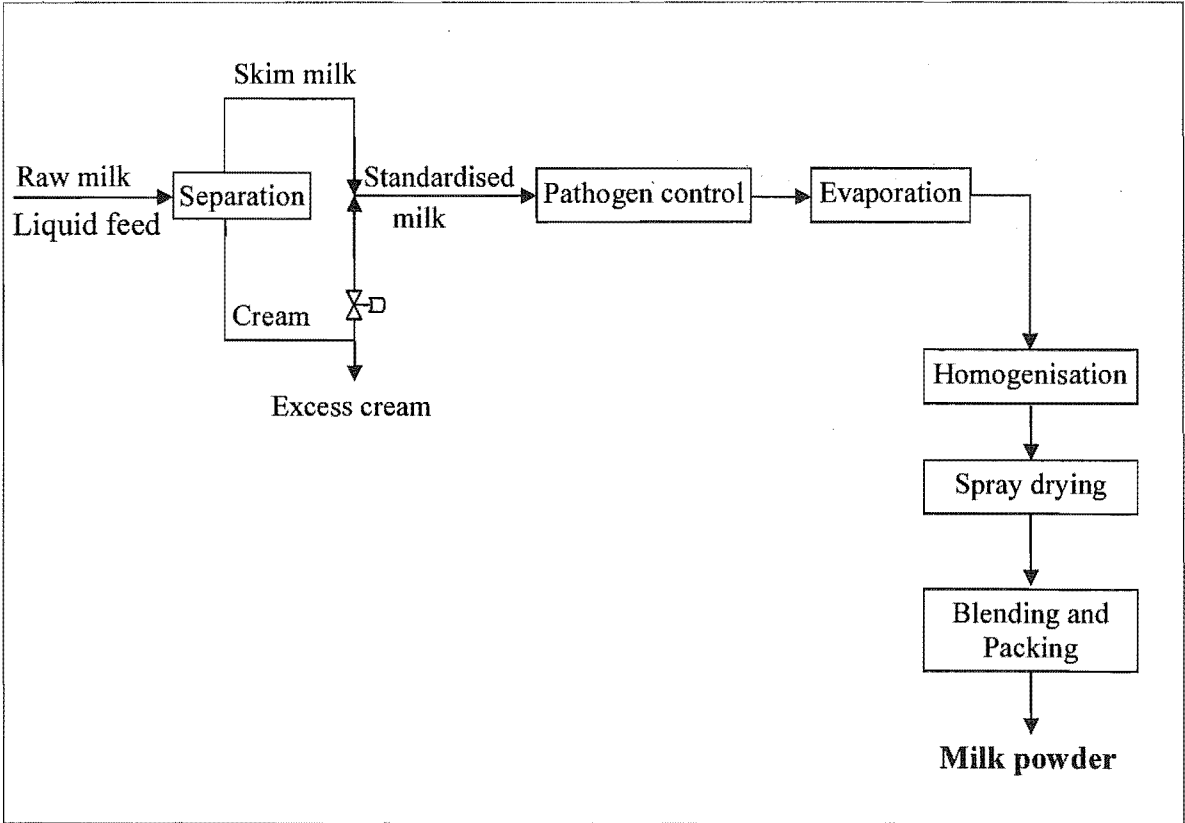


Figure 5-10 Schematic typical flowsheet of whole milk production.

Each powder has a slightly different composition and/or set of processes as shown in Table 5-7.

Table 5-7 Process operations of the most common powder products.

Process operations	Milk powder products				
	<i>SMP</i>	<i>ISMP</i>	<i>WMP</i>	<i>AWMP</i>	<i>IWMP</i>
Separation	✓	✓	✓	✓	✓
Protein standardisation	✓	✓			
Protein and fat standardisation			✓	✓	✓
Vitamin addition			✓	✓	✓
Preheating and pasteurisation	✓	✓	✓	✓	✓
Evaporation	✓	✓	✓	✓	✓
Homogenisation			✓	✓	✓
Concentrate heating	✓	✓	✓	✓	✓
Atomisation and drying	✓	✓	✓	✓	✓
Classification and agglomeration		✓		✓	✓
Powder cooling	✓	✓	✓	✓	✓
Sifting	✓	✓	✓	✓	✓
Blending	✓		✓		
Gassing or gas flushing and packing			✓	✓	✓
Packing	✓	✓	✓	✓	✓

5.5.2 Production Requirements and Constraints

One of the main drivers in the selection of process components is the high-energy consumption required to remove water from milk, especially when it involves the phase change of evaporation. Spray drying (described in Section 4.2.4) is currently used in producing milk powder. Water is normally removed from the milk by evaporation, which takes the solids concentration up to the maximum feasible for this process.

A constraint on the operation of water removal steps is the heat-sensitivity of milk products, so the product temperature must be kept below about 70 °C with short residence times.

Economics encourage the use of continuous processes but no such constraint is imposed by specific requirements of the product.

Typically, spray driers use air at about 180 °C, which requires an energy source with a temperature of at least 200 °C. This can be provided by high pressure steam, hot heat transfer oil or combustion gases. A TVR evaporator will require a lot of steam while an MVR evaporator will require a lot of electrical power. The selection of the energy source for these processes must be done in conjunction with the energy requirements for other parts of the plant. In some cases, co-generation of steam and electricity provides an integrated solution.

5.5.3 Special Powders

Two special powders are described here: cheese powder and baby formula.

5.5.3.1 Cheese Powder Process

Cheese powder offers an effective way to add cheese flavour to a product. The primary application of dairy-based products in the snack food industry is for seasoning and flavourings because they enhance the flavour and the appearance of snacks. Cheese powder is used in coatings, dips, dry mixes, salad dressings, sauces, soups, crackers and many other formulations in the food industry.

Cheese powder is generally custom designed, and developed specifically to satisfy the needs of the snack manufactures. An example specification is given in Table 5-8 (Chandan, 1997). Cheese powder may also be supplemented with a stronger spice flavour and appearance.

Table 5-8 Specification example for cheese powder.

Component	Specification
Moisture	3% maximum
Fat	30 -35% or variable
Salt	6-8%
pH	5.0 to 5.5

Processing of Cheese Powder

There are two common methods of processing cheese powder. The first method is by maceration of cheese. The cheese is dispersed in water at a 35% to 40% solid concentration with emulsifying salts. Dry milk, whey and vegetable oils can also be

added. It is then homogenised and the concentrate is spray dried by atomising it in a hot air stream. Cheese powder collected in this way is expensive compared to the original dried cheese blends, which are just dehydrated cheese. For example, hard Italian parmesan cheese is dried after grating in tray or belt dryers to reduce moisture to less than 6%. After cooling, this cheese is ground and packaged.

The second method of cheese processing involves the treatment of raw cheese curd with specific lipases and proteases along with fermentation by a cheese culture. The cheese paste is then heated to stop the reaction before being cooled. It is called enzyme modified cheese and can be sold as a paste or blended as in the first method, and spray dried into a cheese powder product.

5.5.3.2 Baby Formula Process

Infant formula based on cows' milk has a composition and nutritive value designed to simulate human milk. The protein and fat composition of cow's milk is modified to make it similar to that of human milk (Chandan, 1997). Commercially available infant formulas are produced to meet nutritional requirements of infants. Other additives may be included e.g., vitamins and whey protein isolates in different proportions (Ahmed *et al.*, 1998).

Quality control is very rigorous with regard to microbial populations, pesticide levels, mineral content and vitamin concentrations (Chandan, 1997). Baby foods are normally formulated from non-fat milk solids, demineralised whey, vegetable oils, lactose and corn syrup solids and/or sucrose. These formulations are wet blended and homogenised before spray drying.

There are major qualitative and quantitative differences in protein, lactose, and mineral (ash) content between cow and human milk as shown in Table 5-9 (Bylund, 1995). Milk is the only food for young mammals during the first period of their lives. The substances in milk provide the infant with both energy and building materials necessary for growth.

Table 5-9 Quantitative composition of cow and human milk (Bylund, 1995).

Milk	Protein total %	Casein %	Whey protein %	Fat %	Lactose %	Ash %
Cow	3.5	2.8	0.7	3.7	4.8	0.7
Human	1.2	0.5	0.7	3.8	7.0	0.2

The conversion of cow’s milk into infant formula generally involves the following (Bylund, 1995; Chandan, 1997):

1. Reducing the minerals, especially the sodium content
2. Reducing the protein level
3. Reducing the casein to whey protein ratio
4. Increasing the lactose content
5. Increasing the vitamin levels
6. Replacing the milk fat with vegetable oil to simulate the fatty acid profile of human milk.

Baby foods are available either in powder, concentrated or ready-to-feed liquid formula (see Figure 5-11).

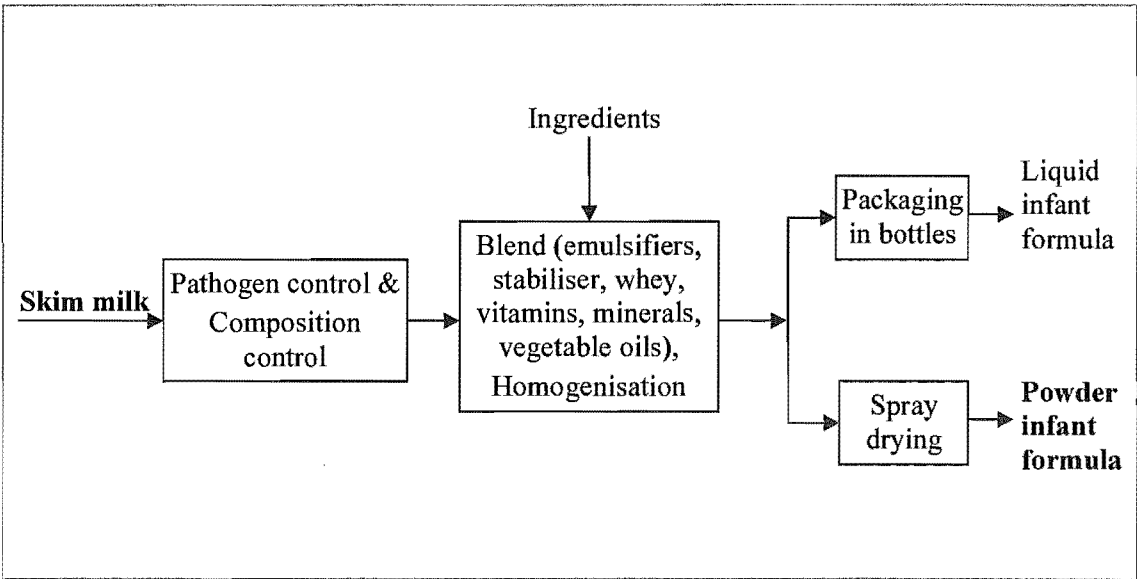


Figure 5-11 Schematic flowsheet of infant formula production.

5.6 **Production of Casein**

The proteins in milk can be broadly classified into two groups, the casein proteins (2.8% of milk) and whey proteins (0.75% of milk). Casein is the protein precipitated from the skim milk by acids or enzymes while the whey protein remains in solution (Hynd, 1975; New Zealand Institute of Chemistry, 1998). All the amino acids that are essential for humans are present in casein in high proportions, with the possible exception of cysteine which is present only in low concentrations (Fox & McSweeney, 1998). Casein may be considered a highly nutritious protein. Casein is a principal component of ordinary cheese but is also separated as a pure protein.

The manufacture of casein from skim milk requires the casein to be separated from the whey components, namely, lactose, whey proteins, fat, minerals and other minor organic components (Hobman, 1978).

Table 5-10 shows that casein proteins are the major milk proteins, constituting 80% of the total milk proteins. Casein proteins are made up of many hundreds of individual amino acids, some of which may have a positive or negative charge (Southward, 1998; Walstra and Jenness, 1984). The amino acid types and their order in the protein molecule determine the nature of the protein. Any change in type or position may result in a protein with different properties. The number of combinations of the 18 amino acids present in milk protein in a chain containing 100 - 200 amino acids creates almost unlimited numbers of proteins with different properties (Bylund, 1995).

Table 5-10 Concentration of milk proteins (Walstra & Jenness, 1984).

Protein	Number of amino acids	Amount of total proteins (w/w)
Casein		
Alpha	406	38.6%
Beta	209	28.4%
Kappa	169	10.1%
Others		2.9%
Total		80%
Whey proteins		
β- Lactoglobulin	162	9.8%
α- Lactalbumin	123	3.7%
Immunoglobulin	100	2.1%
Others		4.4%
Total		20%

Until the 1960s the major uses of casein were in technical, non-food applications such as adhesives for wood, in paper coating for high quality printing paper, leather finishing and in synthetic fibres, as well as plastics for buttons, buckles, photo resist etc. (Southward 1986; Muller, 1971). Nowadays, casein is used as an ingredient in foods to enhance their functional properties, such as whipping and foaming, water binding and thickening, emulsification and texture, and to improve their nutrition, including weight loss and weight gain beverages and to make imitation cheese (Southward & Walker 1980).

5.6.1 Casein Process

Skim milk is the raw material that has previously been separated from whole milk and has been through a pathogen control step. Cream is the co-product from the initial separation. The casein protein is precipitated to form a coagulum, it is heated (cooked), then the curd is separated from the whey and is washed several times with water prior to mechanical dewatering (Southward & Walker, 1980). The casein-making process is shown in Figure 5-12. Three types of casein are produced and named in accordance with the coagulating agent employed, namely lactic acid casein, mineral acid casein and rennet casein.

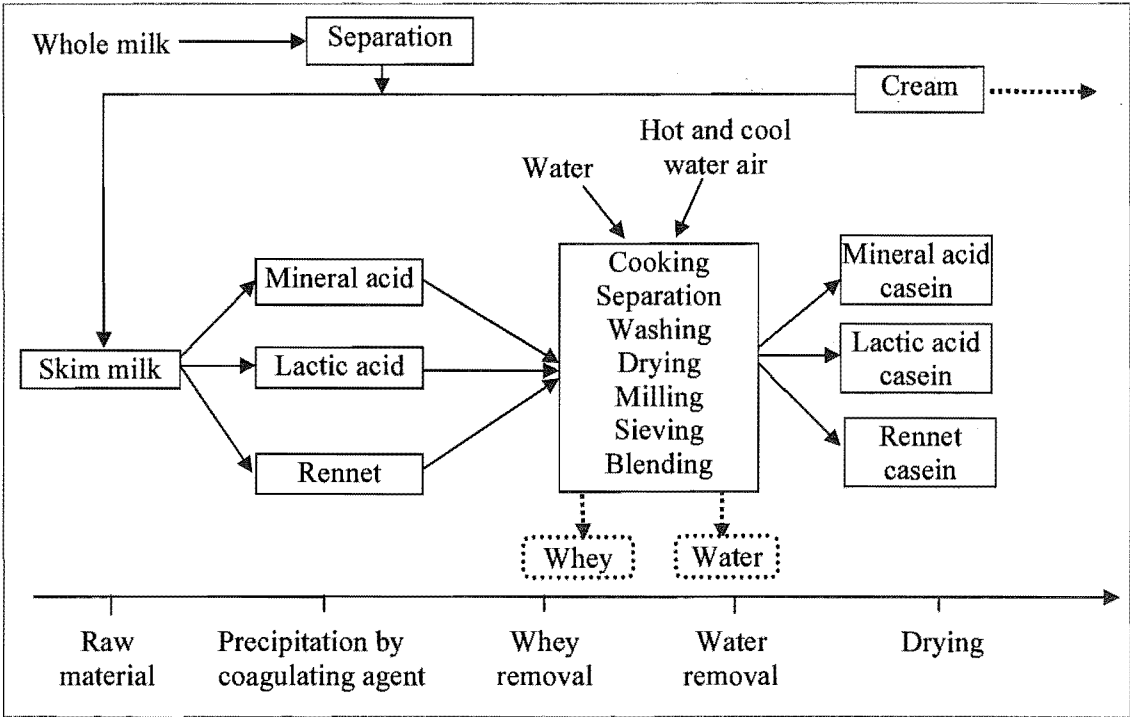


Figure 5-12 Generalised flowsheet of mineral acid, lactic acid and rennet casein production.

The properties of different types of acid casein are very similar and for most applications, the acid casein can be used interchangeably, although lactic acid casein is perceived to be more natural in some markets. Acid casein and rennet casein have the co-product whey that is generally classified as acid whey or sweet whey (neutral pH).

Mineral Acid Casein Production

For the precipitation of mineral acid casein, warm pasteurised skim milk at a pH of 6.7 is mixed with dilute hydrochloric or sulphuric acid to reduce the pH to approximately 4.7. The casein is precipitated as individual particles in a liquid serum (whey), unlike the gel/coagulum formed in lactic acid casein manufacture (Southward, 1998). The acidified milk mixture is then heated, held in a tubular flow device or vat and processed in the standard manner described below.

In Australia and Europe, the most common precipitant for acid casein is hydrochloric acid, which is a by-product of the chemical industry and hence is relatively cheap. In New Zealand, however, sulphuric acid is relatively cheap, because it is produced in comparatively large quantities by the fertiliser industry for use in the manufacture of superphosphate (Southward, 1998). Consequently, mineral acid casein is precipitated using sulphuric acid in New Zealand.

Lactic Acid Casein Production

For the traditional manufacture of lactic acid casein, skim milk is first pasteurised at 72 °C for 15 seconds. It is then cooled to a setting temperature of 22 °C to 26 °C and inoculated with several strains of lactic acid producing bacteria known as the starter bacteria. The milk is then held without agitation in silos for a period of about 16 hours while the bacteria turn some of the lactose in the milk into lactic acid (Southward, 1998). This reduces the pH to about 4.7, causing the coagulation of casein.

The coagulum is then heated to a temperature of about 50 °C, and followed by a brief period of residence in a cooking line and “acidulation vat”.

Rennet Casein Production

The skim milk is not acidified, but the pH remains at about 6.7 throughout the manufacturing process. Following the pasteurisation of the skim milk, it is cooled to a setting temperature of about 29 °C. The calf rennet or microbial rennet is then added and mixed thoroughly. During the stage of renneting, the enzyme specifically cleaves one of the bonds in κ -casein, releasing part of the protein chain that is commonly referred to as glycomacropeptide (GMP) (Southward, 1998). The renneting reaction usually takes 20 to 40 minutes. The coagulated milk may then be cooked and processed as described below.

Casein Powder Process Description

After the casein has been precipitated by any of the above methods, it agglomerates to form a gel or loose clumps of casein (curd). Heating (cooking) of the precipitated casein causes the particles to shrink and expel moisture (whey). The casein is then separated from the whey by screen filtration described Hobman & Elston (1976) (see also Section 4.2.1) or centrifugal decanters and washed several times with warm water at 30 °C to 35 °C to reduce the lactose and salts content (Figure 5-13). The lactose removal is essential so that the casein does not discolour later via the Maillard browning reaction (Fox & McSweeney, 1998; O’Brien, 1997). Counter-current multi-stage washing is often used to remove residual whey and lactose from the casein. The water content is reduced after the last washing stage by roller pressing or centrifuging. Wash water from casein processing can be recovered by reverse osmosis for reuse within the plant. The casein product is granular at this stage with a moisture content of about 50% and is either dried or passed onto a caseinating process described below.

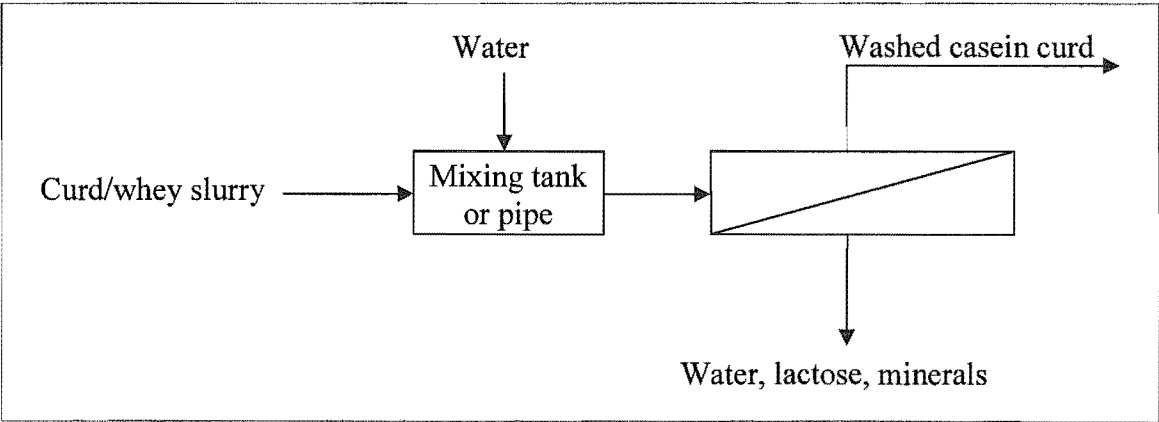


Figure 5-13 Schematic of a single stage of casein washing.

Vibrating fluidised bed driers, with one or more decks, and pneumatic-conveying ring driers have been found suitable for drying casein to its equilibrium moisture content of 8% to 12% (Bylund, 1995; Kessler, 1981). The dry processing stage includes moisture equilibration, size control and blending and packing. The warm and unmilled casein from the dryer is normally cooled (perhaps by air conveying) and circulated to ensure that moisture is well distributed within and between particles. It is then milled, sifted (to separate different particle sizes) and blended (to ensure uniformity). The casein is finally packed. Washing and drying casein involve moisture equilibration; size control, blending according of the client requirements. Figure 5-14 shows the casein powder flowsheet.

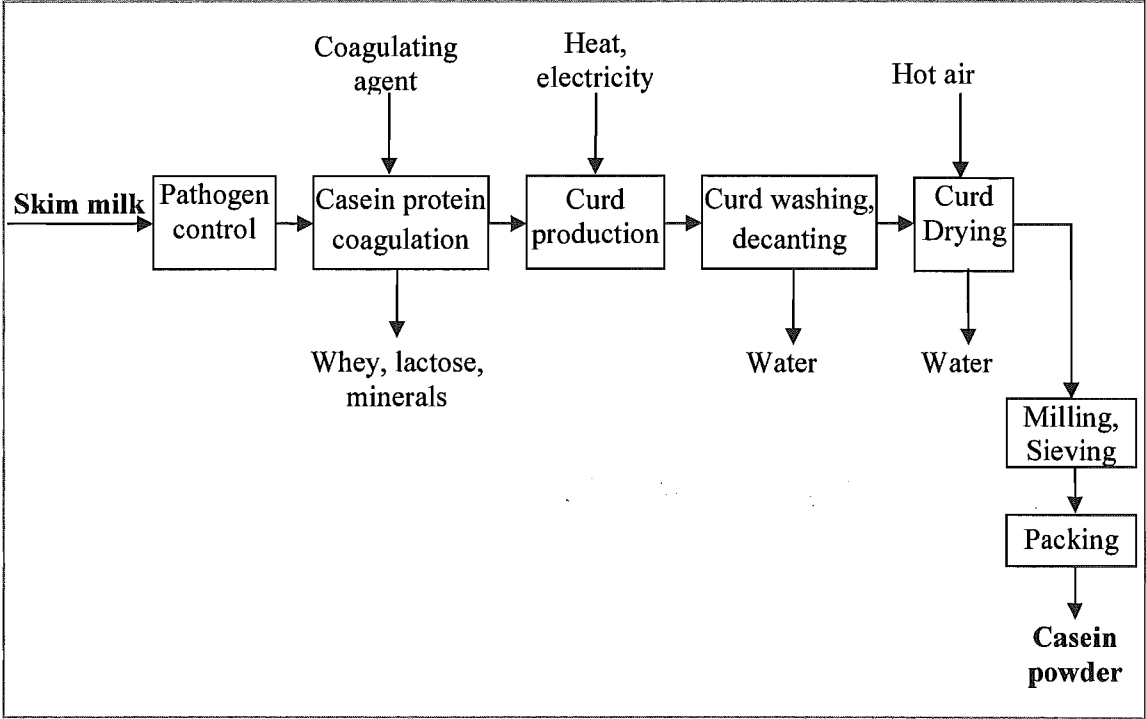


Figure 5-14 Schematic flowsheet of casein powder production.

5.6.2 Caseinate Process

Caseinates are water-soluble derivatives of acid caseins, produced by the reaction of either fresh acid casein curd or dried acid casein with alkalis. The most common alkali used is sodium hydroxide solution but calcium, potassium and ammonium hydroxides are also used. (Southward, 1998; Muller, 1971) The usual amount of sodium hydroxide needed is about 1% (w/w) of the casein solids. Dried acid casein curd is milled and mixed with the alkali using high shear.

In the manufacture of sodium caseinate from fresh casein curd, it is essential to dissolve the casein completely. Casein curd is mixed with water and suspensions of casein in water are disintegrated in a colloid mill. Sodium hydroxide is then added to the slurry, which is subsequently heated and agitated to effect conversion into sodium caseinate solution (Muller, 1971). Casein reacts readily with sodium hydroxide to produce sodium caseinate (Towler, 1976). The resulting solution is generally spray dried to produce a caseinate powder with a moisture content of 3% to 6% (see Figure 5-15).

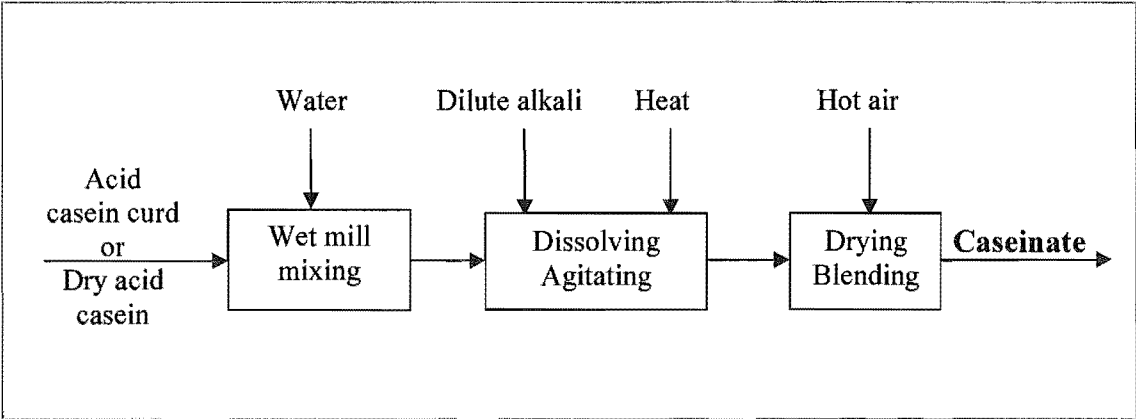


Figure 5-15 Schematic flowsheet of caseinate production.

Caseinate solutions have a high viscosity, so it is difficult to achieve a total solids content of more than 20%. The high-energy requirements of spray drying mean that a high total solids content is desirable and thus the viscosity needs to be taken to the practically allowed maximum. The design needs to take into account the difficulty of mixing and pumping. A high temperature (up to 95 °C) is used during the later dissolving stages to reduce the viscosity of the sodium caseinate solution and to increase the reaction rate.

Sodium caseinate is easily dissolved in water and is used in many ways in the food industry in confectionery, pasta products and meat products (Spreer, 1995). Ammonium caseinate can be used in the preparation of “photo resist materials”, i.e., solutions with photographic compounds.

5.6.2.1 β -Casein Fraction Process

There is an enormous interest in developing techniques for the fractionation of caseins on an industrial scale for special applications, e.g., β -casein has very high surface activity and may find special applications as an emulsifier or foaming agent. Human milk contains β -casein but only at a low level. Hence, the β -casein depleted product from cows' milk is an attractive ingredient for milk-based baby food formula (Fox & McSweeney, 1998).

The β -casein is the most hydrophobic of the caseins. Up to 80% of the β -casein may be recovered from milk or dilute sodium caseinate solution by (loose) ultrafiltration at 2 °C and the β -casein may be recovered from the permeate by (tight) ultrafiltration at 40 °C (Pearce, 1992; Fox & McSweeney, 1998) (see Figure 5-16).

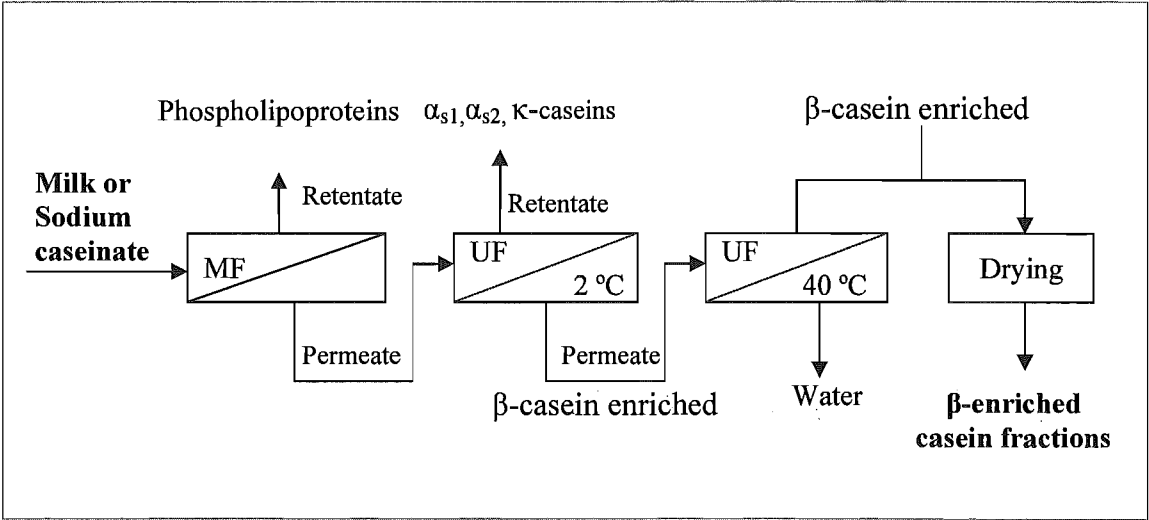


Figure 5-16 Schematic β -casein enriched fractions flowsheet.

The fractionation of β -casein also can be achieved by different methods such as ion-exchange adsorption, selective precipitation with CaCl_2 (Fox & McSweeney 1998).

5.7 Production of Cheese

Cheese has been made by many cultures since ancient times. It has been and is still being made using the traditional methods of preserving foods by fermentation, dehydration and salting. Cheese is a milk concentrate of mainly casein protein, fat and moisture, with very little whey protein or lactose. The basic technology for the manufacture of all types of cheese is similar; relatively small changes in procedures during manufacture result in large perceived differences in the final cheese (Tamime, 1986; Varnam & Sutherland, 1994). Cheese is consumed fresh or at different stages of ripening, often after it is moulded, pressed, and salted, and had colorants, herbs and spices added (Spreer, 1998).

Morison (1997a) defined cheese manufacture as a separation and reaction process. He described the cheese making process using a system of equations based on the mass balance around each of the individual components of the cheese making process. His model provides a useful engineering approach to understanding clearly the complexity of cheese production (Figure 5-17).

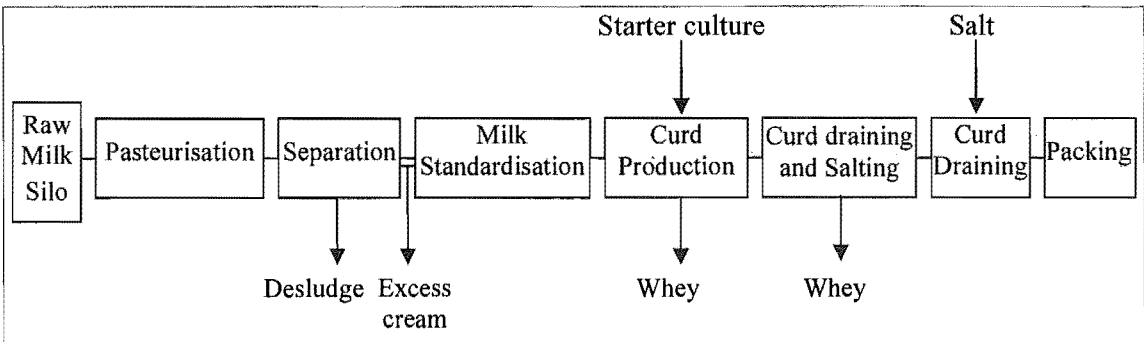


Figure 5-17 Schematic of cheese production flowsheet, Morison (1997a).

There is an enormous range of cheeses on the market. Worldwide, there are more than 2000 types of cheese (Spreer, 1998), which can be classified into different groups such as type of milk, shape and weight of cheese, type of rind, method of coagulation, consistency of cheese, fat content, method of preparation and maturation (Tamime, 1986). See the following classification.

1. *Cured or ripened cheese*; this must be held for months to enable the necessary biochemical and physical changes that characterise the cheese. The ripening rooms

must have the temperature and humidity appropriate for each type of cheese, and ripening time is needed (Kessler, 1981). Different regions of the world have evolved varieties of cheese types some of them are shown in Table 5-11. This table gives also average values for storage temperature conditions and ripening storage time of some extra hard, hard, semi-hard and semi-soft cheeses.

2. *Mould cured or mould-ripened cheese*; the curing has been accomplished primarily by the development of characteristic mould growth throughout the interior and/or on the cheese surface (Shaw, 1986).

3. *Uncured, unripened or fresh cheese*; the manufacture is similar to that of rennet cheese, but it has a high degree of acidity and it is not subjected to a proteolytic ripening process (Spreer, 1998). This cheese is ready for consumption shortly after manufacture.

All cheese, apart from fresh cheese goes through a series of microbiological, biochemical and physical processes cycle called ripening (Bylund, 1995). Ripening is caused by bacteria or by yeast and/or moulds and their enzymes (Kessler, 1981). Ripening varies widely between hard, medium-soft and soft cheeses and even within these groups.

Table 5-11 Origin of the main cheese types in the world (Bylund, 1995; Kessler, 1981).

Type	Country of origin	Fat on dry basis	Moisture % in fat free basis	Ripening storage time	Temp. of ripening	Texture
Parmesan	I	35+ %	≈ 40%	1-2 years	10-15 °C	Extra hard
Grana	I	35+ %	≈ 41%	1-2 years	10-15 °C	Extra hard
Emmenthal	CH	45+ %	≈ 52%	9 months	12-18 °C	Hard
Gruyere	F	45+ %	≈ 52.5%	9 months	12-18 °C	Hard
Cheddar	UK	50+ %	≈ 55%	4-12 months	4-8 °C	Hard/Semi-hard
Gouda	NL	45+ %	≈ 57%	2-12 months	12-15 °C	Semi-hard
Tilsiter	D	45+ %	≈ 57%	2-3 weeks	10-12 °C	Semi-hard
Havarti	DK	45+ %	≈ 59%	2-12 months	12-15 °C	Semi-hard
Blue cheese	DK, F, S	50+ %	≈ 61%	5-8 weeks	9-12 °C	Semi-hard or Semi-soft
Brie	F	45+ %	≈ 68%	5-8 weeks	9-12 °C	Semi-soft
Cottage	USA	> 10 %	< 69%	---	---	Soft

I-Italy, CH-Switzerland, UK-United Kingdom, NL-Netherlands, D-Germany, DK-Denmark, F-France, S-Spain, USA- United States of America.

5.7.1 Cheese Making Process

Cheese making involves a number of main stages that are commonly used in most types of cheese. There should first be a pathogen control step (normally pasteurisation), not only for food safety but also to enable the added cheese starter bacteria to grow without competition. Separation is required to produce the skim milk and cream streams, which are later recombined to obtain a process feed with a standardised fat content. Standardisation of the protein content or protein to fat ratio is also possible by adding a protein enriched stream (perhaps produced by UF, Section 4.2.1.2). The rennet and the starter culture are mixed into the standardised milk in a vat, causing the milk to set and the pH to drop. Once set, the coagulum is cut and heated to form the curd (Vickers, 1968). The whey is separated from the curds either by draining it from the vat or by pumping the curd/whey slurry onto the draining belts or into moulds. All the cheese making process steps up to this point are common for all cheeses. The method of salting depends on the cheese type. Salting can be achieved by adding salt to the whey, to the curd, or onto the rind, placing the cheese in brine, or in whey and brine (Kessler, 1981). In brine salting, the cheese is placed in a container with brine, i.e., any system at about 12 °C to 14 °C (Bylund, 1995). The curd can be salted and mixed in the vat or on a belt (dry salt). The curd is then formed into blocks of standard weight before it is packed. Excessive handling particularly during vat filling, cutting the curd and pumping operations will result in increased fat and casein losses in the whey (Phelan, 1981; Chapman, 1981; Callanan, 1991). A typical dry salt cheese making process is shown in Figure 5-18.

If cheese-making is considered purely as a chemical and physical process, the flowsheet can be represented conceptually (dry salted cheeses) as shown in Figure 5.18, where a primary liquid feed stream (milk) is processed via a number of operations to obtain a solid product with specified functionality for a customer. Warm water is used only for some cheeses.

The moisture content of the cheese serves to distinguish various categories, such as the hard (low-moisture), semi hard and soft cheeses. Each category is further distinguished by a number of characteristics, such as the structure (texture, body), flavour and appearance, which depend on the choice of bacteria and technique employed. The moisture level depends on the operating conditions used. The moisture content of

cheese is a significant factor in the production quality and profitability of a cheese making process, as it is the cheapest components of cheese, higher moisture should yield higher profits.

Seasonal variation in the composition of milk protein can have a significant influence on the cheese yield, and also the percentage of fat recovery varies between 85% and 93% depending on the system used (Phelan, 1981; Callanan, 1991).

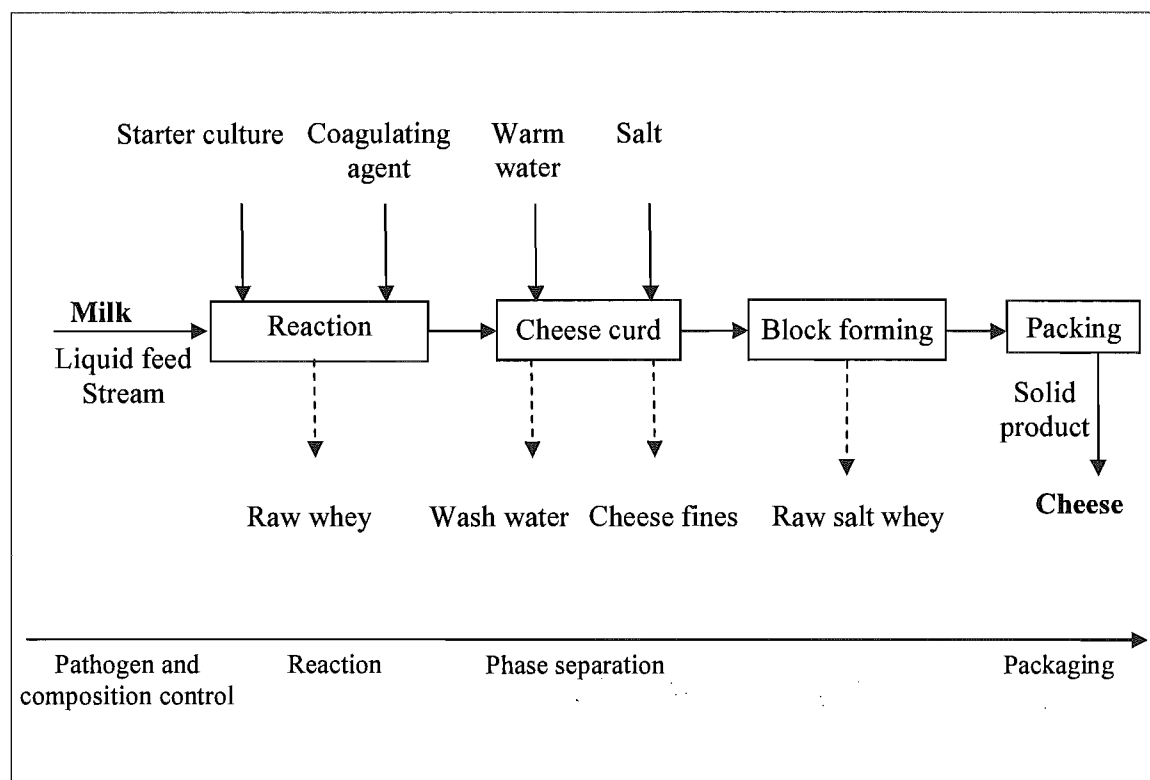


Figure 5-18 Conceptual representation of dry salt cheese production.

5.7.2 Production Requirements and Constraints

Pathogen control (pasteurisation) of the liquid feed may be required for health reasons and often in order to satisfy local regulations. The product quality can be measured by five variables in order to determine how well the cheese conforms to the specification (Jones, 1999). These are pH, salt, moisture, fat and sensory evaluation.

Sodium chloride is added for three distinct purposes. Firstly, the salt influences processes which affects acid development by inhibiting the action of the starter and many of the characteristics of the cheese (Spreer, 1998). Secondly, salt improves the consistency of the cheese. Finally, it also improves the flavour. Manufacture and

maturation of cheese seems to be impossible without lactic bacteria. Growth of most of the lactic bacteria is also slowed if not stopped by the addition of salt (Walstra *et al.*, 1999).

5.8 Production of Whey Protein Products

For a long time, whey was regarded as no more than a waste product of conventional cheese making. Now however, it is used as a co-product with valuable nutrients and of economic importance in the efficient utilisation of the raw material (milk). In recent years, utilising whey derived ingredients such as whey proteins for functionality and nutritional value has made whey a profitable resource.

Whey protein in general, and α -lactalbumin in particular, has very high nutritional value. Whey protein is the milk serum protein that is produced after the separation of casein and fat during the manufacture of cheese and also after the casein is coagulated by acid. Sweet whey, which is rennet whey can be distinguished from acid whey, which is a result of acid coagulation (Spreer, 1998; Zadow, 1986) (see Section 5.6.2). Production of cheese leaves about 85% of the milk volume as whey, which contains whey proteins, lactose, salts in solution and water.

Whey proteins can be recovered from the whey by salting out, dialysis or ultrafiltration (Fox & McSweeney, 1998). Whey can also be recovered by heat precipitation at 37 °C or salting-out method, where saturation with NaCl at 37 °C precipitates not just the casein but also the immunoglobulins because the immunoglobulins are among the most heat-sensitive components of the whey proteins (Fox & McSweeney, 1998). The majority of whey proteins remain soluble, provided they are undenatured.

Whey concentration by RO (which reduces transport costs) and whey fractionation by UF (which produces a whey protein concentrate which is a valuable co-product) have become the largest membrane applications in the food industry today (Mannapperuma, 1997; Hobman, 1992).

Deproteinized whey or serum derived from the whey plant, whey from the production of cheese and whey from the production of casein are a potential source of lactose for lactose powder and non-alcoholic beverages (Short, 1978).

Cheese fines (casein and fat residues) and lipid residue often interfere with the membrane separation processes and impair the functionality of whey protein products (Korhonen *et al.*, 1998). Methods based on centrifugal separation, heat treatment or microfiltration have been developed to remove fines and lipids from whey.

The applications for whey products are increasing with more advanced separation techniques. Rather than dealing with all the variety of whey applications, here only the manufacture of whey powder, whey protein concentrate, whey protein isolate, lactoferrin and α -lactalbumin will be described, although the manufacture of individual ingredients will also be cited.

5.8.1 Whey Products Processes

The raw material for whey protein or whey protein concentrate is sweet whey or acid whey. There are two basic issues that become evident in both processes. One of these issues is the high water content of whey about 93.4% wt (Rudd *et al.*, 1973) and the other is its very short life because of high bacterial levels.

Processing whey has long been a problem, especially as the cheese industry has grown. Initially, in a small-scale cheese production, the whey was used to feed animals, in what could be termed a by-product and animal integration. Then, as cheese production increased, the disposal of large volumes of whey took the next alternative of integration, which was the land disposal for crops production and pasture. This also became a problem when the cost of widespread application was high. The land can be also constrained by disposal regulations in order to maintain a clean environment. Thus, the opportunities of whey processing appear as an alternative to effluent treatment (see Figure 5-19). The initial cost of whey processes were initially high but with the advancement of technology, whey products have become very important alternative co-products that generate high revenue. Although whey mostly consists of water, it also contains many of milk's nutrients (Archer, 1998). Fractions of whey are designated as α -fraction, the aggregate phase, and the β -fraction, the soluble phase (Pearce, 1992;

Varnam & Sutherland, 1994), as shown in Figure 5-19. However, some processes for manufacturing these whey-based products for food and non-food uses are economically feasible only for larger sized processing operations, with an adequate supply of consistently high-quality whey, and adequate market demand for the products (Morr, 1992; Jelen, 1992).

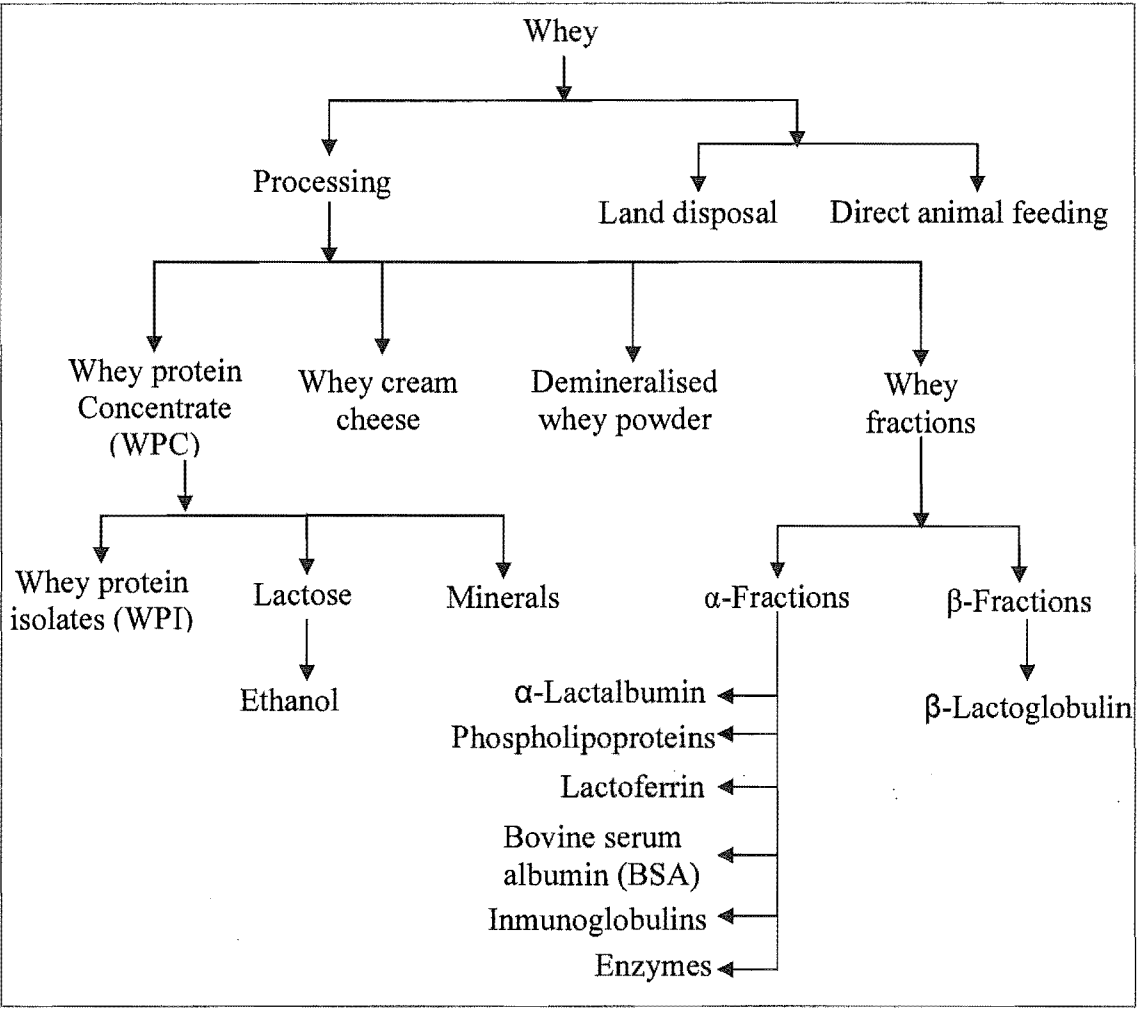


Figure 5-19 Schematic representation of some whey use opportunities.

5.8.2 Whey Protein Concentrate (WPC) Process

Whey protein concentrates are products derived from whey by removing the curd fines (casein and fat residues), minerals, lactose, and water. Whey is recovered from cheese or casein manufacture operation it is inevitable that low levels of “curd” fines are present in the whey, which has a serious risk of blocking heat exchanger channels, and ultrafiltration and reverse osmosis membranes (Pearce, 1992; Matthews, 1984). Therefore, clarification of raw milk is achieved by either combination of settling, screening and centrifugation.

The processes of protein concentration use membrane separation (ultrafiltration), electrodialysis and ion exchange technologies (Section 4.2). The advantage of ultrafiltration is that the protein remains in its original state and there is no thermal or pH effect. The concentrate is generally spray dried afterwards to produce a whey protein concentrate (WPC) powder (see Figure 5-20).

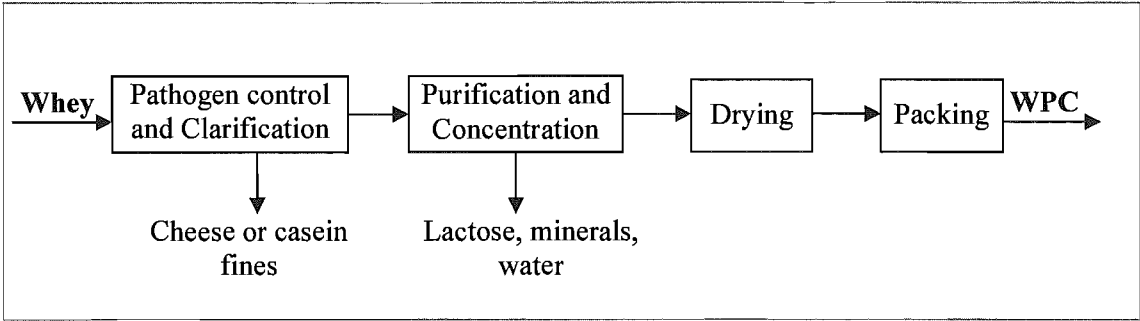


Figure 5-20 Schematic of WPC production flowsheet.

Whey protein concentrate containing 50% to 80% protein has two major uses. It is used by food manufacturers to take the advantage of the whey protein’s gelling properties particularly in soups (it provides excellent functionality in terms of water binding, thickening and emulsifying) and in bakery products where it is also available in a gel-forming version which is used as an economical egg white replacement. Secondly, whey protein concentrate has a very high nutritional value, it is especially suited for use in meat replacers, sports bars, dietary foods, nutritional drinks and protein-fortified beverages (Zall, 1992). On a dry basis, the protein concentrate contains a minimum of 25% protein and whey protein isolates contain at least 92% protein (Chandan, 1997).

5.8.3 Whey Protein Isolates (WPI) Process

Whey protein can be further purified by microfiltration (see Section 4.2.1.2) or ion exchange (see Section 4.2.5) to produce a whey protein isolate (WPI). This product contains over 92% protein and is used as a nutritional supplement in cultured dairy products.

The production of highly purified protein from whey is called whey protein isolates (WPI). Whey protein isolates contain 90% to 95% proteins. WPI is a high value product. The functional properties of WPI are superior to those of whey protein concentrates on an equiprotein basis due to a lower level of lipids, lactose and salts;

their production is limited by higher production costs (Fox & McSweeney, 1998). The functional properties include foam stability and total solubility over a range of pH's producing a clear solution compared with the turbidity that occurs with fat containing milk products. When WPI is whipped, it forms a foam which is equivalent to that produced by fresh egg white both in its foam volume and stability (Palmer, 1977).

The process of whey protein isolates involves the isolation of protein from solution by means of ion exchange resins, which offers an effective method for the production of whey protein isolates (Palmer, 1977; Hervé, 1974; Jones, 1974; Ayers *et al.*, 2003). These ion exchangers have the ability to selectively adsorb, great quantities of high molecular weight materials, in particular proteins from solution (Palmer, 1977). Protein may be recovered from the resin when this is exhausted by regenerating the bed (Grant, 1974).

The β -lactoglobulin is a major protein in cows' milk, it represents about 50% of total whey protein and 12% of the total protein in milk (Fox & McSweeney). A number of methods have been developed for the separation of α -lactalbumin fractions and β -lactoglobulin fractions (Etzel, 1999; Kuwata & Ohtomo, 1989).

The whey protein isolates can be also processed from whey by using ion exchange chromatography, and precipitation using FeCl_3 or polyphosphates (Fox & McSweeney, 1998).

5.8.4 Special Whey Proteins

Whey proteins possess interesting functional properties, nutritional, physiological and pharmaceutical properties. Special proteins can be also flavourful. Consumers may not always realise that this category of products does indeed come from milk, e.g. the natural antibacterial lactoferrin protein. Thermal fractionation of whey can be used in the production of two main whey proteins fractions, the α fractions and the β -fractions (Varnam & Sutherland, 1994). These protein fractions have specific functional properties widely used in the food industry. Mozaffar *et al.* (2000) provide methods and compositions for the sequential separation of whey protein fractions.

5.8.4.1 Lactoferrin Process

Lactoferrin is a natural antibacterial and anti viral protein (Bloore, 2001). Lactoferrin protein is an inhibitor of bacteria. This inhibition is caused by the removal of iron ions from the serum. Lactoferrin has good solubility and binds iron so strongly that it is not available for pathogens (Korhonen *et al.*, 1998).

Many biological functions of lactoferrin have been reported; the bacteriostatic effect of lactoferrin being perhaps the most significant of its biological functions (Abe *et al.*, 1991). Lactoferrin provides a wide range of benefits in oral health care and it is suggested that toothpaste (Fox & McSweeney, 1998) be fortified with proteins such as lactoferrin to promote superior oral hygiene.

Human milk has a higher lactoferrin content than cows' milk (Walstra *et al.*, 1999). Therefore, there is considerable interest in supplementing cows' milk based infant formulae with lactoferrin. The concentration of lactoferrin in colostrum is about 1250 mg/kg. In mid lactation, the concentration falls to less than 100 mg/kg in cow's milk (Walstra & Jenness, 1984).

Figure 5-21 shows a simplified method patent by Ahmed *et al.* (1998), a sequential separation of whey proteins using radial-flow chromatography, where lactoferrin is one of the protein fractions isolated from whey.

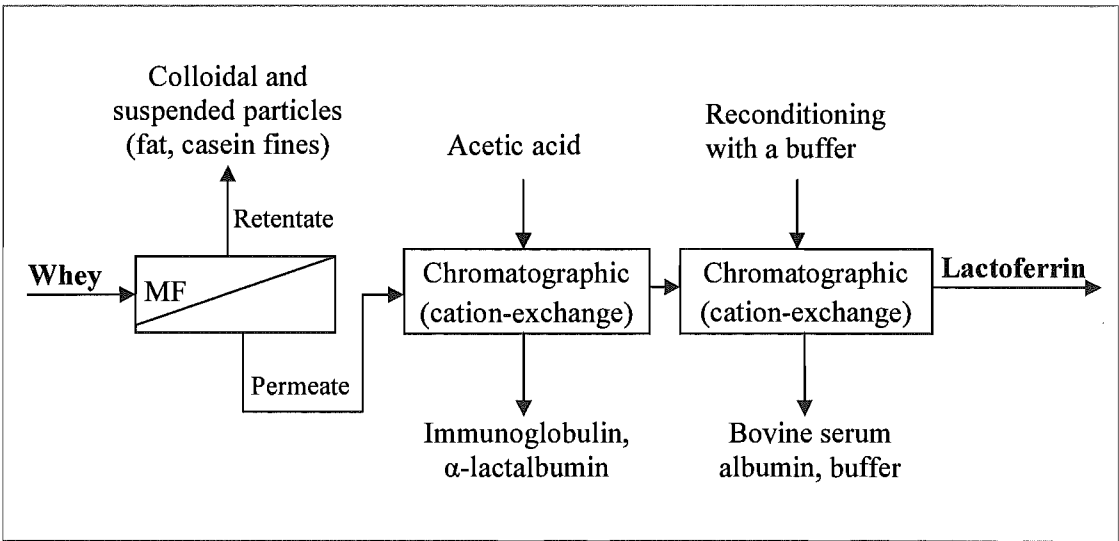


Figure 5-21 Lactoferrin process flowsheet (adapted from Ahmed *et al.*, 1998).

5.8.4.2 α -Lactalbumin Protein Fraction Process

The α -lactalbumin fraction is one of the two main whey protein fractions, representing about 20% of total whey protein. α -Lactalbumin is the most abundant protein in human milk, therefore α -lactalbumin is widely used as a source as a highly humanised infant food (Varnam & Sutherland, 1994). The concentration of lactose in milk is directly related to the concentration of α -lactalbumin as its biological function is as a coenzyme in the synthesis of lactose (Walstra *et al.*, 1999).

The α -lactalbumin is present at low concentrations and is hence relatively expensive to produce (Fox & McSweeney, 1998). These proteins can be used in a variety of nutritional designed products, a few examples of which are breakfast cereals, nutrition bars, dietary beverages and general food fortification. These proteins take on the flavour of anything they come in contact with so they fit very well with whatever product is being designed.

Processing of α -Lactalbumin

Figure 5-22 shows the heat denaturation of the proteins in acid or rennet whey, usually at about 90 °C. Whey protein is heated at an acidic pH of about 6 (Fox & McSweeney, 1998) and precipitated as α -lactalbumin. The precipitate is recovered by settling, decanting, centrifugating or filtering processes. Washing may be used to reduce the lactose and mineral content before the drying takes place in a spray drier, fluidised bed or roller drier, in order to recover up to 90% of the original protein. The conditions used vary according to the types of whey and the properties that are required in the final product (Varnam & Sutherland, 1994).

The α -lactalbumin proteins are very hygroscopic and will lump badly and become unusable in the presence of moisture if not properly sealed during storage.

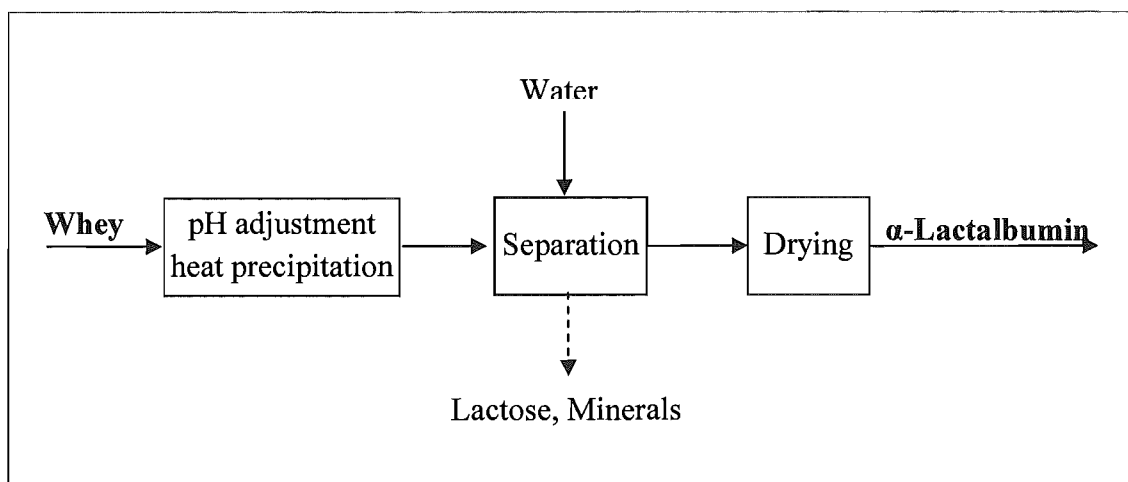


Figure 5-22 Schematic α -lactalbumin process flowsheet.

The α -lactalbumin can also be fractionated from whey by a single cation exchanger, and using different pH values for eluting different protein fractions without using salt elution (Etzel, 1999).

5.8.5 Production Requirements and Constraints

Whey can be protected against rapid spoilage by chilling it to 4 °C. This allows storage for a few hours before it is further processed. It can also be heat treated, although this can cause protein denaturation (de Witt & Klarenbeek, 1983). In some countries, preservatives such as 0.05% hydrogen peroxide or 0.5% sodium or magnesium sulphite are added.

5.9 Production of Lactose

Lactose, commonly referred to as “milk sugar”, is the principal carbohydrate in milk. If lactose is the major constituent of most of the dried dairy-based products, i.e., 37% in whole milk powder, 50% in skim milk powder, 50% in butter milk powder, and 70% in whey powder (Holsinger, 1997).

The disposal of the lactose component of whey used to be a worldwide problem in any country with a large dairy industry. Although the liquid has only 4% to 5% lactose (milk sugar), this is enough to cause a significant environmental impact because of its very high biological oxygen demand (BOD).

Large quantities of lactose in whey are produced as a co-product from the manufacture of cheese and casein or as a co-product of whey protein concentrate production. This must be disposed of or processed in an environmentally acceptable way.

Lactose is now used as a product of rich diversity and a variety of grades are available. It is used extensively in the pharmaceutical industries in its most highly purified form as a coating agent and to give bulk to pills and tablets, ensuring they are large enough for people to handle (Harper, 1992), and in the formulation of nutritional health foods believed to enhance health and well-being. Lactose is used in the food industry to increase the viscosity or to improve texture without making the product too sweet since it possesses a mildly sweet taste compared with fructose and saccharose. However, hydrolysis of lactose makes considerably sweeter products (Bylund, 1995). Lactose is used in beer manufacture because it is not fermented by yeast. Since it remains in the finished product, it helps increase the viscosity and improve the mouth-feel and flavour (Holsinger, 1997). It has similar uses in other dairy beverages and foods such as toppings, icing, and pie fillings (Chandan, 1997). Lactose can also be fermented into alcohol, which is then distilled to remove impurities and used in gin, and other spirits. A major use is in humanised infant formula where the balance between carbohydrate and protein in cows' milk can be corrected by the addition of lactose (Holsinger, 1997). It is also used as a fermentation substrate for the production of a variety of products, i.e., cheese, lactic acid casein, and yoghurt. Another more recent major use is for the standardisation of milk powder to maintain a constant protein fraction lower than that naturally occurring in most milk.

5.9.1 Lactose Process

There are three methods proposed for the commercial production of lactose. They are crystallisation from a supersaturated solution, precipitation by alkaline earth minerals and precipitation by solvents, such as alcohol. The most common is the crystallisation method described as follows.

Lactose is generally produced from rennet whey or from whey permeate obtained by ultrafiltration of milk or whey. The manufacture of lactose (see Figure 5.23) involves concentration to high total solids, deproteinisation and demineralisation of whey using membrane separation processes such as ultrafiltration, nanofiltration reverse osmosis

(see Section 4.2.1.), or by evaporation (see Section 4.2.3). The mineral content is often reduced by either electrodialysis and/or ion exchange. A supersaturated solution is cooled under specific conditions to crystallise the lactose, the crystals formed are harvested, washed to remove the mother liquor, and dried. The product obtained in this way contains 98% lactose (Chandan, 1997). To obtain lactose with a higher purity, the product is redissolved and crystallised to remove colours, proteins, salts and odours (Kessler, 1981). The particle size of lactose depends on its intended application.

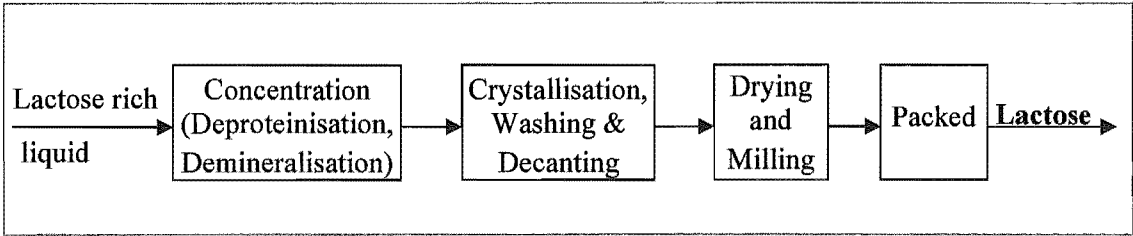


Figure 5-23 Schematic flowsheet of lactose production.

The yield and purity of the crystals are affected by the protein and mineral content of the starting material. For this reason, it is best to start with deproteinised, and demineralised whey. The removal of minerals by ion exchange or electrodialysis improves the heat transfer in the evaporator by reducing deposit formation and permitting concentration to 75% totals solids (Holsinger, 1997). Crystallised lactose needs to be purified by washing with pure water in the centrifuge to produce crude lactose. The grades of lactose obtainable are: technical 90% to 92%, crude 95% to 98%, food grade 98% and pharmaceutical grade 99.5% to 99.9% (Kessler, 1981). Figure 5-24 shows the conceptual inputs and outputs for lactose processing.

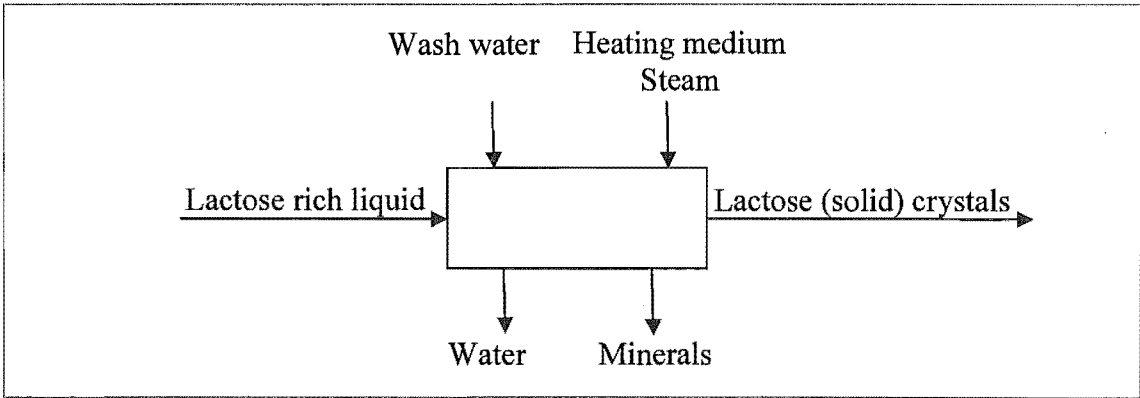


Figure 5-24 Conceptual representation of lactose production.

5.9.2 Products from Lactose

The principal derivatives of lactose have been covered in many publications including Thelwall (1997) and Morr (1992). Figure 5-25 shows some of the products from lactose, two of which are discussed below.

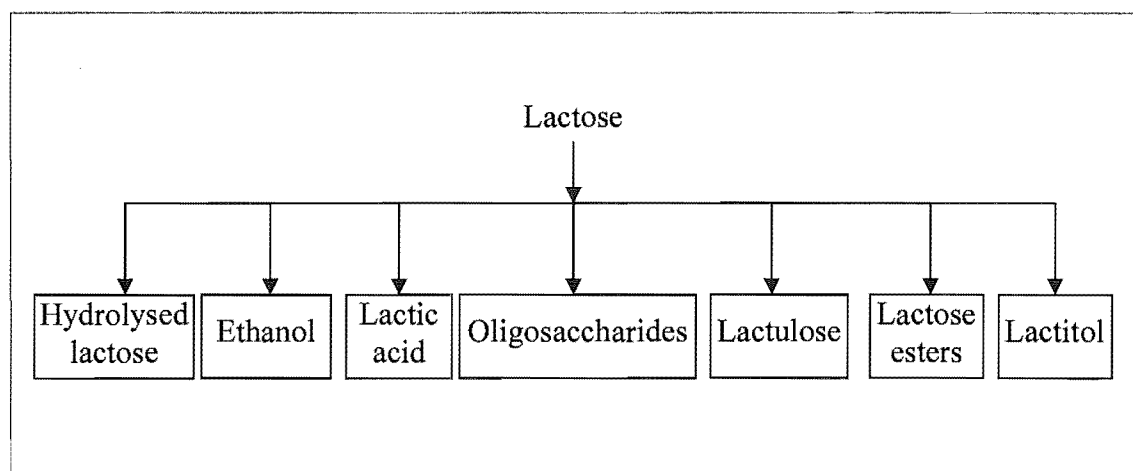


Figure 5-25 Schematic representation of some lactose use opportunities.

5.9.3 Production Requirements and Constraints

Moisture control is essential for maintaining quality. Commercial grade lactose needs to be purifying from water, protein, lactic acid and mineral matter which are attached to the surface and crevices of the crystals. Lactose production needs to maximise the crystallisation to maximise the yield.

5.9.4 Hydrolysed Lactose

Lactose hydrolysis offers the dairy industry a range of products with desirable functional properties, and has increased the consumption of milk in people who have lactose intolerance, also hydrolysed lactose is sweeter and more soluble than the original material.

In the process of hydrolysis, the disaccharide lactose is converted, either chemically by means of acids in conjunction with a heat treatment or by enzymes (β -galactosidases, commonly called lactase), to its two component monosaccharides, glucose and galactose (Fox & McSweeney, 1998; Zadow, 1992).

The drying of hydrolysed lactose is more difficult than normal lactose counterpart because of the presence of high content of its monosaccharides which form glasses in

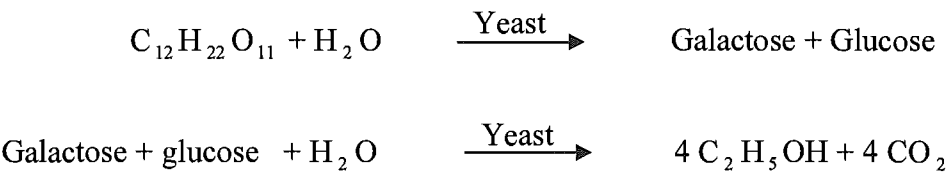
the drying chamber making a sticky product (Zadow, 1992). Production of hydrolysed lactose has been discussed by many publications including Mahoney (1997) and Zadow (1992).

5.9.5 Production of Ethanol

Traditionally, ethanol has been produced using molasses, cane sugar or grain. These raw materials provide the sugar source, which is converted by yeast into alcohol. Whey contains about 5% lactose, which is broken down by lactose-specific yeasts into ethanol. Ethanol is an ingredient in a wide range of products including beverages, cosmetics, printing inks and white vinegar, pharmaceuticals and industrial solvent.

Ethanol Process Description

A lactose-rich stream is the source of carbon and energy for the ethanol production. Yeast is added to ferment the lactose at about 37 °C in two reactions. Firstly, the lactose is split into the two sugars, galactose and glucose. These sugars are then fermented into ethanol.



After that, the yeast is removed from the liquid, which is then distilled to produce alcohol of different purities for a variety of uses (see Figure 5-26).

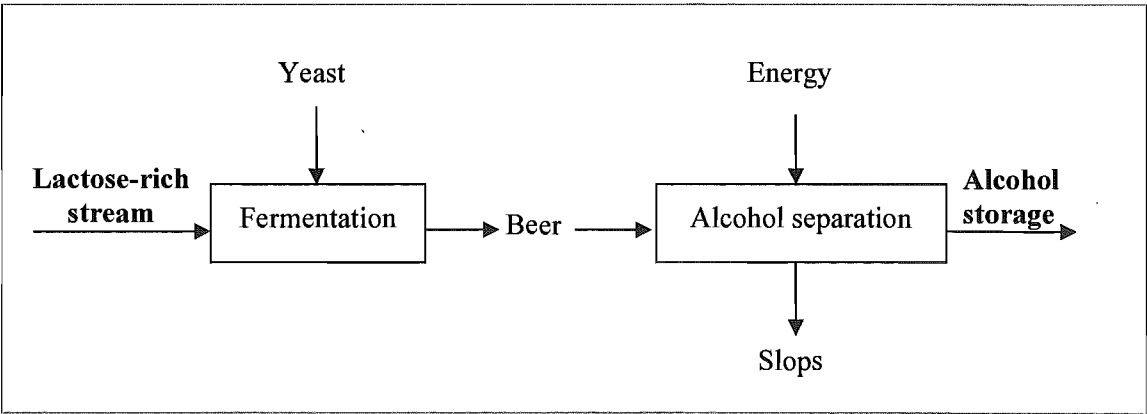


Figure 5-26 Schematic of alcohol production flowsheet.

The recovery of ethanol from a past waste stream (whey) is a good example of process design applied to rectify a problem. New Zealand now produces much more ethanol from lactose than it needs. More than half of the total production is exported to overseas markets.

6 Integration Based Design

6.1 Definition of process Integration

Process integration is the common term used for the application of methodologies for system-oriented and integrated approaches for both new and retrofit applications. Process integration allows feed material, energy, the environment, utilities and time to be related to the whole process rather than being considered as isolated units. According to the International Energy Agency (1993), process integration is defined as the “systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects”. The emphasis is on energy and the environment. The IEA (1993) has added to this definition of process integration a description of the physical arrangement of equipment and the process stream interconnections in a plant. Process integration is considered to be a major strategic design and planning technology by leading companies in the process industry (Gundersen, 2002; Morgan, 1992). Process integration is a relatively new area for engineering design methodology. Until recently, engineers developed conceptual process designs by experience and intuition without using methodology (Linnhoff *et al.*, 1994).

Different types of process integration can be applied to for the design of dairy processes:

- Product and component integration,
- Energy integration,
- Water integration,
- Time integration,
- Clean-in-place integration,
- Environmental integration.

Rising material and energy costs in recent years have increased the economic incentive to employ material and energy integration within a chemical process. These trends have resulted in a greater interaction among process units which were previously studied individually as isolated parts of the entire system (Luyben & Flodas, 1994; and Perkins, 2001). One example of integration is the heat exchanger networks, which replace inefficient uncoupled units (Carlsson *et al.*, 1993; Tjoe & Linnhoff, 1986; Linnhoff & Morari, 1982).

Modern processes are designed to be more efficient in terms of energy and raw material usage, implying a higher level of integration (Perkins, 1989; Kenez, 1998). Pinch analysis, promoted by Linnhoff during the 1980s and early 1990s, was one of the first systematic assessment techniques for the design of heat exchanger networks. It required complex process flowsheets that were not only thermally efficient but also industrially acceptable. Despite being refined by various researchers (Townsend & Linnhoff, 1983; Kemp, 1986; Kotjabasakis & Linnhoff, 1986; Smith & Patel, 1987), this methodology was restricted to identifying heat integration opportunities only. Since then pinch analysis has evolved, its scope has broadened and its application has changed. The scope today includes separation, waste removal and utility systems, within processes as well as total sites. Pinch analysis, originally developed for the heat recovery systems, is now an important concept that initiates the field of process integration (Polley, 1993; Linnhoff, 1994; Polley, 2002).

In addition, increased product yield through loss minimisation reduces effluent production through recycling and recovery. More recently, society measures such as environment effects and sustainability, have become an integral part of the process integration.

6.2 Types of Process Integration

There are two general types of process integration. These are “within” and “between” integration concepts.

6.2.1 Integration “within” an Operation

Most industrial chemical engineering processes consist of a series of standard unit operations. Each unit operation meets the operation objectives independently within a process but contains many different processes. This integration is very well identified and used in the dairy industry. An example is the regeneration section of the pasteurizer, where raw milk is preheated by the milk coming from the heating section. Another example is the multi-effect evaporator which uses thermal vapour recompression and/or mechanical vapour recompression to reuse energy in the vapour.

6.2.2 Integration “within” a Process

A process is a group of operations that together transform a feed material into a product. Integration within the process is possible and often required. The flow of components must be integrated between operations within the process to ensure that the product has the correct composition and that the throughputs are matched. The operating times of each operation must be integrated to minimise storage times and to maximise throughput.

There are likely to be opportunities for energy and water integration as heat or cold water from one operation can be used in another. Cleaning requirements can be integrated, e.g., by providing one “CIP kitchen” for many different operations in the process.

Figure 6-1 shows product (salt) and water integration (reuse) within a brine salt cheese process.

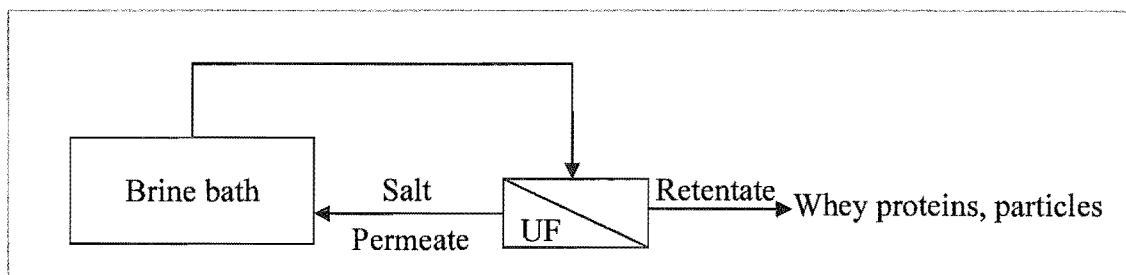


Figure 6-1 Product integration within a brine salt cheese process.

6.2.3 Integration “between” Processes (same site)

Standardisation is a good example of integration “between” processes. Figure 6-2 shows product integration between three processes on the same site.

a) Fat standardisation

- Cream is used to adjust the fat level in the milk and the excess cream is sent to the butter plant.

b) Protein standardisation

- Milk UF permeate is another source of lactose added to reduce the protein level in the milk for milk powder production.
- Milk UF retentate is added to increase the protein level in cheese milk.

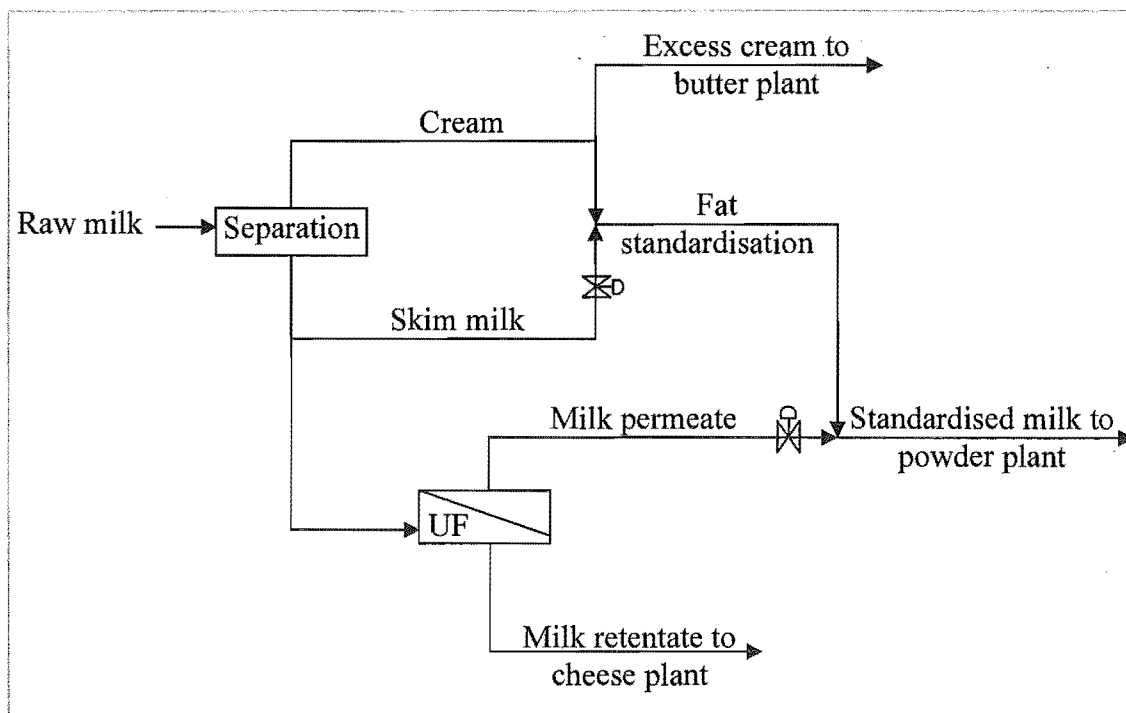


Figure 6-2 Product integration between three processes on the same site.

1. **Process integration of materials between processes** involves sending the co-product streams to other parts of the process. For example, excess cream may be transferred from whole milk powder production to the butter plant.

2. **Utilities integration between processes.** The integration of utilities in an operation is well-identified within processes, although integration between processes still presents a challenge because of the time shifted processes. For example, hot water from any process such as WPC, lactose and cheese milk treatment to the main storage for the CIP kitchen area (French, 2003).

6.2.4 Integration “between” Sites

Integration between sites refers to sending the co-products or by-products to other factories to be further processed. For example, sending whey permeate to a lactose plant, or cream to the dairy ice cream plant.

Process integration between sites would be restrained to product, co-product and by-product integration. Energy, utilities would probably not be appropriate because of the geographic separation.

6.2.5 Integration “between” Dairy Processing and Other Activities

The level of integration between dairy processing, environment and agricultural activities depends on the scale, and this varies widely among communities. Cheese has been made for years and the disposal of the whey in large scale operations was a major concern. While in small scale operations generally, the best alternative for the whey is for it to be fed to pigs. In this instance, there is integration with animal production.

The most common areas of integration between the dairy industry, animal and pasture production is in animal feed and crop applications.

Sustainable agricultural production needs to be matched with sustainable consumption. Sustainable development was defined in 1987 by the Brundtland Commission as “Development that meets the needs of the present without compromising the ability of future generation to meet their own needs” (Arthur D. Little Inc., 2001). However, in an increasingly globalised economy, agricultural companies will only survive if they can develop a competitive advantage that appeals to consumers (Luostarinen, 1998).

This presents both challenge and an opportunity. A competitive advantage exists for someone who combines the needs of customers and the environment. Therefore there is a pressing need for a methodology to integrate dairy processing and other agricultural activities.

Table 6-1 summarises some examples of process integration, within and between same site and between different sites as described above.

Table 6-1 Examples of different types of process integration.

Integration	Same site			Different Sites
	Within		Between	Between
	An operation	A process	Processes	
Product	Standardisation	Brine Salt / UF	Lactose to milk powder	Whey permeate to lactose plant
Energy	Past.regeneration, Evap. multieffect	Pinch integration	Cogeneration	Cogeneration
Water/Effluent	CIP reuse	RO water to CIP	Evap.condensate to boiler	
Time	Pasteurisation	Crystallisation	Cheese / WPC	Cream / Ice cream
Environment	Air heating	Bag house	Cheese whey to WPC	

6.3 Application Areas for Process Integration

Process integration can be applied to the following aspects during the methodology for the design of dairy processes.

6.3.1 Product and Component Integration

Product and component integration is particularly important in the dairy industry and is one of the main focuses of this thesis. Consequently, it is considered in detail in the remainder of this work.

In synthesis, after choosing the main product based on the market, one can identify the basic product choices shown in Table 6-2 in relation to their milk component

composition. For a medium scale process, if one wants to produce casein or caseinates as a first product from whole milk, this leaves other major milk components. The designer may choose butter or AMF as a co-product and still have lactose, minerals and water. Lactose can be processed after the minerals, and water can be recovered and utilised as the water brought onto the site as a component of milk. Milk is about 87.3 % moisture, so a substantial volume of water can be recovered from whole milk powder, skim milk powder and other dried milk products.

Table 6-2 Basic product choices from milk.

Products	Milk major components					
	Fat	Casein	Lactose	Whey proteins	Minerals	Water
Whole liquid milk	✓	✓	✓	✓	✓	✓
Stock food	✓	✓	✓	✓	✓	
Whole milk powder	✓	✓	✓	✓	✓	
Skim liquid milk		✓	✓	✓	✓	✓
Skim milk powder		✓	✓	✓	✓	
Whey powder			✓	✓	✓	
Whey protein concentrate				✓		
Whey protein isolates				✓		
Anhydrous milk fat	✓					
Butter	✓					
Butter milk		✓	✓	✓	✓	✓
Cheese	✓	✓				✓
Casein, caseinates		✓				
Lactose crystals			✓			
Water						✓

Once one decides on one main product (based on the market) then by difference there are other milk components left over for allocation. For example, cheese leaves whey for processing; casein leaves whey and fat for processing.

6.3.2 Energy Integration in Dairy Industry

The dairy industry is a large consumer of energy. This leads to the necessity for an efficient use of energy within an operation, within a process unit and between processes in order to reduce the capital and operating costs.

Any dairy process operation will require some heating and cooling. Some of this can be provided from within and between processes or from another source. Thermodynamic concepts can be applied to find the maximum amount of heat that can be recovered from a system with process integration (Smith *et al.*, 2001; Horlock, 1997). Coal, natural gas and electricity are still the main energy sources used by dairy process operations.

Energy conservation has always been important in process design. The objective is to identify the thermal design of the process to find the energy supply and demand.

Process heat integration generally starts with the generation of the hot and cold composite curves for the process. These curves provide a pictorial representation of overall heating and cooling demands. By superimposing the composites, one can immediately see the scope for heat recovery and hot and cold utility demand (Polley, 1993). Techniques have been developed that minimise the heat needs of a process.

The supply and demand energy should follow certain procedures on the design methodology. French (2003) has proposed a prioritisation sequence of guidelines for heat integration.

- It starts with the identification of product-to-product heat integration options within process unit options.
- This is followed by the identification of product-to-product heat integration options between process units.
- It ends with the determination of available hot water supplies and demands within and between process units.

However, French stated that integration between processes will generally require a larger investment in capital for implementation. This is because of the time shifted processes that need storage (due to process scheduling issues), as well as additional piping and instrumentation (related to the distance between the process units). Furthermore, food safety concerns of product cross-contamination may also exist. Therefore, options for local process integration should be explored first. French also

found pinch temperatures of process units and combinations of process units as shown in Table 6-3.

Table 6-3 Pinch temperatures (French, 2003).

Process unit(s)	Pinch temperature (°C)
Cheese	14
WPC	17
Lactose	50
Cheese, WPC & Lactose	50
Milk Powder	60
AMF	15
Milk Powder & AMF	60
Combined site	15

A dairy process requires a variety of different forms of energy including hot air, steam, hot water, electricity, compressed air, cooling and refrigeration. There are numerous combinations of energy sources possible, especially with evaporation and drying. The evaporator may be a thermal vapour recompression (TVR) type requiring steam at about 10 bar and a small amount of electricity, or it may be a mechanical vapour recompression (MVR) type requiring a significant amount of electricity and a small amount of steam. The dryer air may be heated by high pressure steam or by combustion of oil or gas. A TVR or MVR evaporator is energy integrated within itself, but energy integration between processes can be achieved through the co-generation of electricity and steam or hot water. Although pinch technology can be applied here, it does not give the complete solution for batch processes.

There is also a special case of energy integration between evaporation and pasteurisation. Through steam compression, vapour from the last stage of the evaporator is often used to supply a part of the heat needed for pasteurisation. Then the pasteurisation and the heating to the required temperature before the evaporation are combined.

The batch or semi-continuous nature of food processing introduces a constraint to energy integration. Start-up and shut-down of processes at different times require that energy be stored or that alternative systems be put in place.

6.3.2.1 Energy for Dairy Processing

The term “cogeneration” is often used when both electric power and useful heat are produced (Ray & Sneesby, 1998; Horlock, 1997). The selection of type of plant not only depends largely on the heat and power ratio but also on the size of the heat and electricity demands. The energy supplied to a thermal power station is more effectively used to produce both electricity and useful heat. In a conventional thermal power station only about one-third of the energy in the coal or oil is converted to electrical power, two-thirds of the energy is thrown away in the form of lukewarm water, to the cooling towers or to rivers or to a sea (Williamson & Wallace, 1979). This means the design and operation of an electric power station with cogeneration, producing of both useful heat and work, improves the energy utilisation of the natural gas or coal feed.

A total energy scheme is developed to achieve an internal balance between the electricity and the heat needs of an industrial process so that all its energy, i.e., electricity and heat needs are met from a single fuel input.

With on-site cogeneration, the primary concern is usually with the process heat requirements and electricity is produced as a co-product in such quantities as can conveniently be obtained (Williamson & Wallace, 1979); a deficit or surplus of electricity can be easily traded.

Figure 6-3 shows a cogeneration representation where HP, MP and LP are high, medium, and low pressure steam respectively. Cogeneration of electric power at the dairy processing site enables co-product heat from power generation to be transformed into process steam for dairy separation processes.

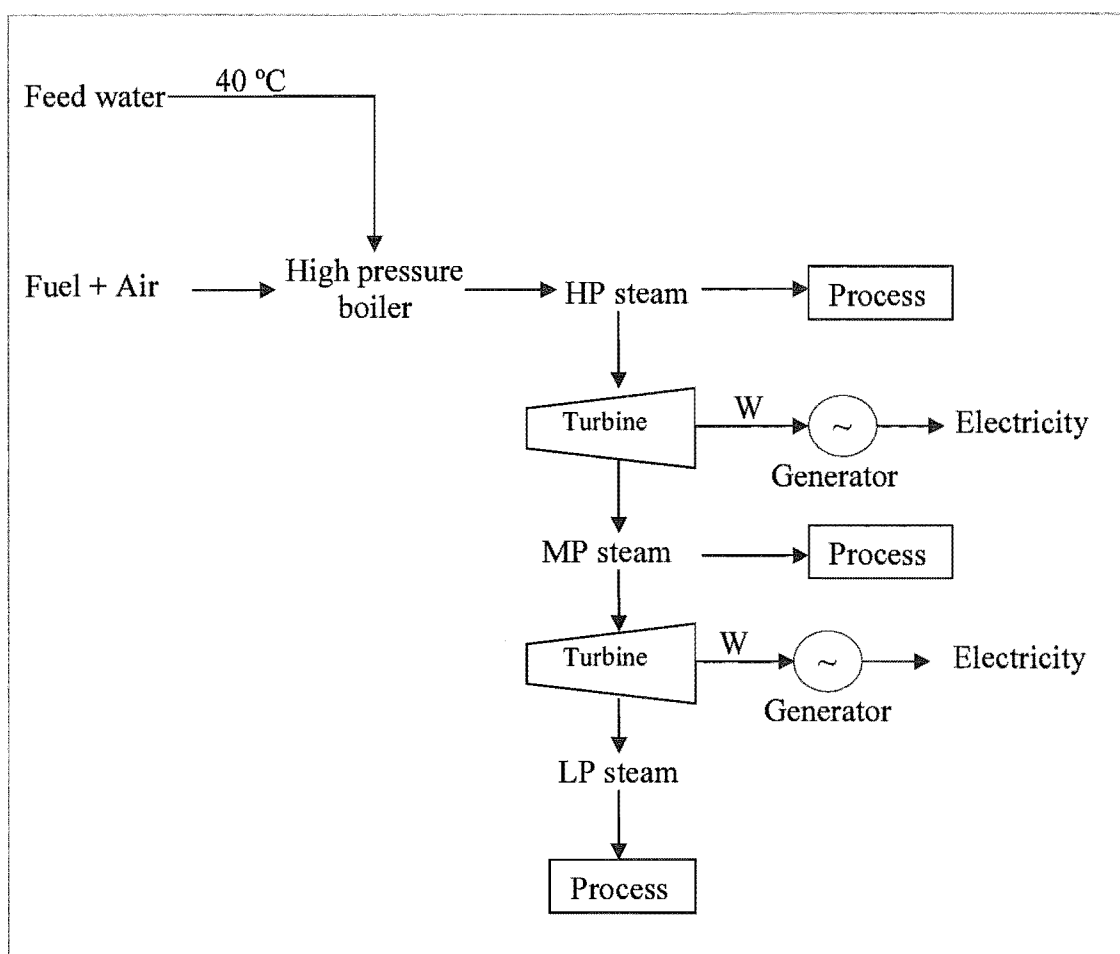


Figure 6-3 Schematic of cogeneration

Processes in the dairy industry require temperatures below 220 °C and frequently below 80 °C. This heat must be generally supplied to the process by combustion of fuels capable of producing flame temperatures in the region of 1800 °C to 2000 °C. Examples of such processes are the drying of milk powder (Section 4.2.4), TVR and MVR evaporation, thermalisation and milk pasteurisation.

Multiple effect evaporators are used to concentrate milk prior to spray drying. They consume a considerable proportion of the energy used by the dairy industry. Heat pumps provide a mean of conserving thermal energy by increasing the temperature of low-grade thermal energy to be used more effectively (Jebson & Lascelles, 1977). A simplified design procedure for energy integration of TVR and MVR evaporators, and spray drying for the milk powder process is shown in Figure 6-4.

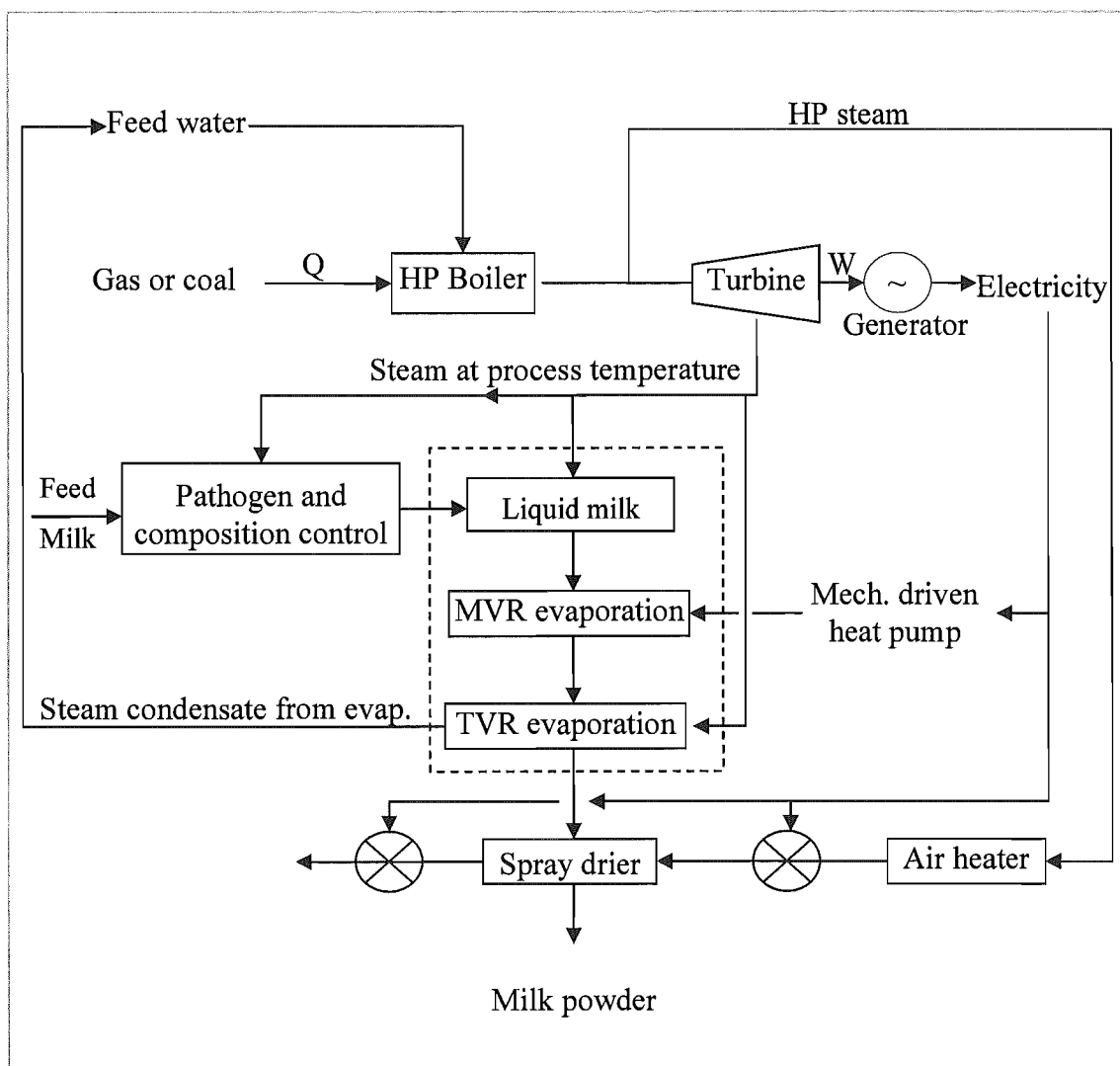


Figure 6-4 Cogeneration and process integration.

6.3.3 Water Integration for Dairy Processing

The cost of wastewater treatment, the shortage of fresh water at many sites, and environmental protection are all persuasive reasons for reducing raw water consumption and wastewater discharge at chemical process plants (Dhole *et al.*, 1996; Feng & Seider, 2001 and Bagajewicz *et al.*, 2000). Water reuse and the regeneration before it goes to waste has led to the reduction of overall water flowrate (Linnhoff *et al.*, 1994). There are numerous opportunities for water recovery and reuse or recycling, especially with RO plants. Likewise, there are opportunities for water minimisation through water recovery and waste segregation.

Water and wastewater minimisation are generic problems of integrated process design. One of the aims of process integration is to make use of all the milk components,

including the water. Dairy process streams contain significant amounts of water. Therefore, water is recognised as one of the valuable components in milk (Roos, 1997).

The options for water integration in dairy processes are defined by a range of qualitative groups of acceptable contamination levels for water 'sinks'. The energy integration method further reduces the options for water reuse because hot water integration is performed first (French, 2003).

Product and utility crossover happen when water becomes both a product and a utility. Generally, while water carries components, it is considered a product. The engineer could consider water to be a product at all stages of processes within the context of component integration. This is a specific example of component integration.

In this study, alternatives are identified for an integrated conceptual design assisted by alternative strategies for dairy industrial water reuse and wastewater minimisation in a systematic effort to reuse water at a plant.

Water Sources for the Dairy Industry

Dairy processing water supplies may be bore water, river water, municipal water systems, or mixed. The dairy industry requires most water to be of potable quality. Some processes (i.e., reverse osmosis and evaporation) produce water by-product streams. These can either be directly used as process streams (e.g., RO permeate) or as utility streams (e.g., evaporator condensate). Utilisation of the water from a reverse osmosis plant will reduce the production demands on both the treated water and demineralised water plants.

Cooling installation systems provide warm water which is normally potable and is sometimes discharged into the storm water piping system.

6.3.3.1 Water Uses in Dairy Industry

When manufacturing milk products, large volumes of water are used for a number of purposes listed below:

1. Process water. Direct contact, e.g., final rinse in the CIP, or washing casein.
2. Heat exchange water. Indirect contact, e.g., cooling water.

3. Clean-in-place water (CIP) including all the cleaning stages of the plant except the final rinse.
4. Pump seal water. The water provides the seal, but on failure of the pump seal the working fluid will pass into the seal water.

Industrial waste water includes spilled milk and its products, and cleaning solutions. The concentration and composition of the wastewater depends on the production programme, operating methods and design of the processing plant. The pH varies between 2 and 12 as a result of the use of acid and alkaline detergent for CIP. Water with a pH of over 10 or below 6.5 must not be discharged into the sewage systems for plants located in cities because, it is liable to corrode the pipes. As a result the detergents normally used are collected in a mixing tank. The pH levels are often measured and regulated to around 7 before being discharged to the drain. The greatest volumes of water effluents are produced by casein protein products followed by whey protein products.

6.3.3.2 Constraints on Water Reuse

In practical applications, there are constraints in reusing water. Some cases are distinguished where problems of water reuse involve the following constraints:

- *Temperature.* In many cases where cooling water has been heated, it cannot be used for cooling in the same temperature range.
- *Microbiological growth when stored.* For time shifted processes, microbial content prohibits reuse of water. For example, water in one process may not be used in another process because of the danger of microbial contamination within or between processes. For example, RO water is warm and often has enough nutrients for the growth of microbes so it needs treatment before it is used. The potential micro-organisms recycling or distribution of potable water used in the dairy industry must be free of pathogenic micro organisms.

Water Treatment or Quality Upgrading

There is abundant information on analysing and designing wastewater treatment systems as well as chemical treatment processes. These include ozonation, chlorination, ultraviolet light with or without the addition of peroxide, as well as on unit operations

such as ion exchange, electrodialysis, and reverse osmosis with possible ultrafiltration or nanofiltration pre-filtering (Stephenson & Blackburn, 1998; Mann & Liu, 1999 and Bes-Piá *et al.*, 2002). There are limits of contamination and chemicals in the water which might be injurious to health (Kessler, 1981; Doyle & Smith, 1997).

6.3.3.3 Water Component Integration

Although milk itself is 87.3% water, the dairy industry uses more water than it processes milk. A large amount of water is transported into the dairy factories in milk. Water can be recovered as milk water condensate from evaporation or permeate from the reverse osmosis processing of cheese, casein and whey protein. This not only facilitates the reuse of a significant waste stream, but also provides a cost effective source of demineralised water, thus reducing the environmental impact by reducing both effluent and fresh water supply flows (Barnett *et al.*, 1997).

Reverse osmosis water is a potential source of demineralised water for cleaning and diafiltration in WPC production where there is a large volume of water usage. RO water has enough nutrients for the growth of microbes so it must be sterilised and not stored for more than about 24 hours. The water sterilization system includes the use of an ultraviolet sterilization unit and the treatment by ozone and chlorination. The water from the reverse osmosis plant needs to have its bacteria counts determined to detect the amount of bacteria present.

In order to reduce water consumption in the dairy industry, the designer needs to find the minimum amount of fresh water that each water-using process needs. Conversely, the objective is to utilise the maximum amount of water effluent from these processes that can be reused in other processes. In this way, effluent discharge volumes will be reduced. Maximising the reuse of water within a process and between processes can be of great help. A systematic methodology can reduce the freshwater usage.

French (2003) proposed a methodology with four stages for water integration in dairy processes.

1. The first stage is to identify water sources and sinks after energy integration procedure has been completed.

2. This is followed by classification of water production and consumption according to location and major source and sinks functions.
3. Then, the balance for water sources and sinks by flow rate is performed; water source and sink matches within process units should be investigated first and excess water source or sink from other plants should then be matched.
4. Finally, if the dirty water reuse options became non-feasible the treatment of dirty water may be considered.

Other opportunities to minimise water consumption in dairy process units may arise from the study and optimisation of water demands through small changes to plant equipment or operation, with little capital investment (French, 2003). For example, by reducing the CIP rinse times and cutting back excess water supplies to plant equipment.

6.3.3.4 Examples of Water Integration

There are three possibilities for water integration:

1. Pinch water integration

Pinch technology has been used successfully to identify water reuse opportunities in the petrochemical industries, which have continuous processes (Wang & Smith, 1994; Dhole *et al.*, 1996). However, the dairy industry tends to have batch and semi-continuous processes and food hygiene requirements that limit the extent to which pinch water integration can be applied. Consequently, most of the water pinch integration is limited to CIP first rinse and chemical make up.

2. Generation and reuse of water

Here a typical example of water reuse is presented.

Figure 6-5 shows skim milk is sent to an RO plant to concentrate the milk for the casein process while also generating water as permeate. Casein making requires large amounts of water to wash lactose and minerals from the casein curd before it is dried (see Section 5.6.1). The reuse of casein wash water is highly desirable. This is technically achievable using an integrated RO plant to reuse the wash water as shown in Figure 6-5. This water reuse integration process works well without the need for storage. This

system also has the advantage of concentrating valuable components of milk solids such as lactose and minerals.

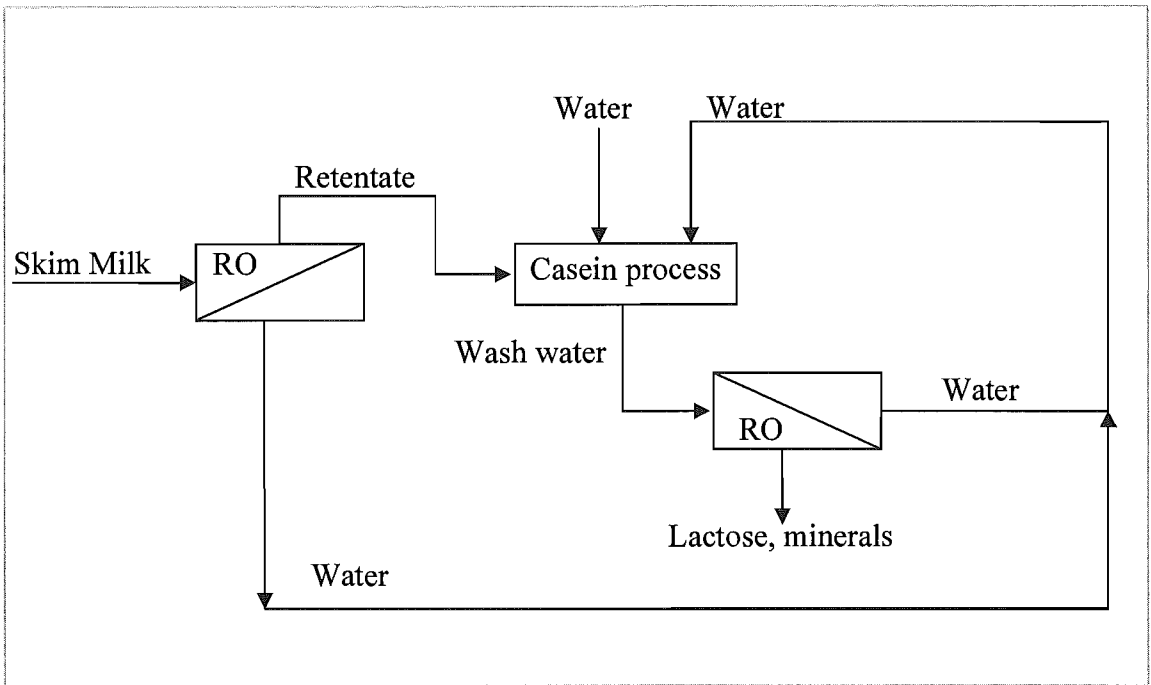


Figure 6-5 Generation and reuse of water milk component.

3. Water Treatment

The dairy products industry today is based on extracting the full value from milk components. Figure 6-6 shows milk water condensate treatment by RO membrane filtration to generate reusable water.

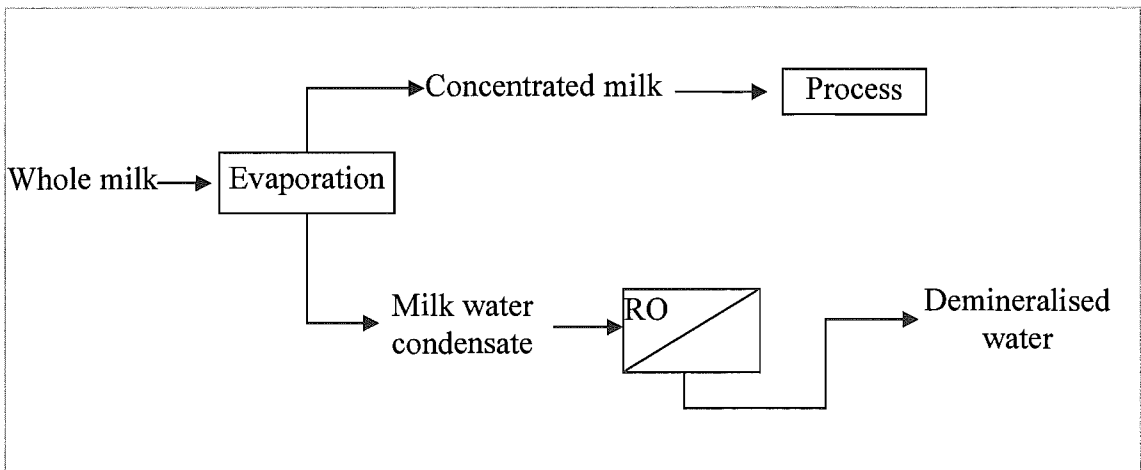


Figure 6-6 Generation of demineralised water

6.3.4 Time Integration

Time integration is the allocation of available time between processes. Time integration or scheduling is part of the design process required to link the production operations.

Classes of Processes with Respect of Time

In this study processes are classified as follows:

1. *Contemporaneous processes* are those in which everything happens at the same time, e.g., evaporation preheat and evaporation condensate production.
2. *Processes separated by a fixed time* are those processes that happen one after the other with a known time in between, e.g., milk treatment and cheese, which both operate on 24-hour cycles.
3. *Processes separated by a limited variable time* are those processes that happen one after the other and the time is limited so that the second process is carried out before the product spoils, e.g., cheese and whey permeate processing.
4. *Time-independent processes* are those where no fixed time is required, e.g., anhydrous milk fat (AMF) from butter.

For heat recovery, no storage is required when the processes are contemporaneous. However, with any processes separated by a fixed time, process separated by limited variable time or time-independent processes, heat storage is required. Therefore, contemporaneous processes are more suitable for heat recovery.

Many process unit operations consist of a mixture of batch, semi-batch and semi-continuous process operations. In some cases, these process operations may be performed in either multipurpose equipment or dedicated equipment (Samsatli & Shah, 1996). Time integration within the process is relatively simple in comparison to the integration between processes. This is because different processes have different run times. Therefore, the integration between processes needs scheduling or storage.

Types of time integration for scheduling products:

Time integration for different products using the same process equipment. Integration may require that the process for one product must be completed before the process for the next product starts.

6.3.4.1 Design for “Schedule Ability”

Defining the schedule must be done during design to ascertain that there is enough time and to see if a continuous process might be better than a batch process. For example, the cheese process has a combination of continuous and batch processes as shown in Figure 6-7.

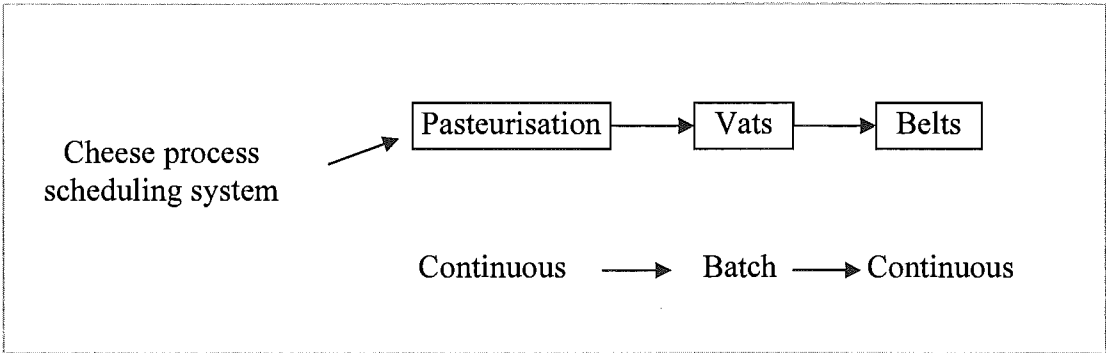


Figure 6-7 Cheese process schedules

Building scheduling systems requires a structured approach to create lists of inter-related processes. They can be contemporaneous processes, time shifted processes by fixed time, time variable processes but with limited time (flexible) or time independent processes. In contrast to energy integration, all classes of processes may have time integration opportunities. In some cases, it would make the time shifted and time variable processes easier, thus allowing extra time to achieve better scheduling options. There are several reasons why the engineer should consider time integration in the process design.

The design for “schedule ability”, which this research is considering, is in response to feed, capacity for advance planning and scheduling process operations.

Issues in Time Integration

- Higher capital investment reduces scheduling problems. Good time integration minimises capital investment.

Product

- Minimum storage reduces problems of pathogen growth and/or microbial control.
- It is important to match capacities of plants to minimise storage time and maximise plant utilisation.

6.3.5 Clean-in-Place Integration

In the dairy industry cleaning is a crucial operation for ensuring hygienic safety of foods and for recovering performances of plant and process such as heat transfer, pressure drops, surface cleanliness (Dresch *et al.*, 2001). There is a special case where cleaning solutions are periodically drained when they are considered to be too polluted (Gésan-Guiziou *et al.*, 2002). It does not apply to once through systems.

Clean-in-place integration (CIP) and/or kitchen integration is another integration opportunity in the dairy industry. The integration of clean-in-place in the dairy processing operations for minimisation of water, chemicals and energy use also requires special consideration and, in some cases, a simplification of general process integration guidelines. There is an option where heat, chemicals and water integration within and between processes during clean-in-place (CIP) is desirable because this can offer significant reductions in energy water and chemical usage (Dresch *et al.*, 2001). CIP integration would also minimise effluent volumes. However, differences in process run times and production sequences make this a difficult task. There are also risks associated with contamination between different parts of the process. Specific CIP chemical requirements (e.g., specialised membrane cleaning chemicals) further complicate the task of CIP integration.

An example of process integration between processes is the reuse of milk condensate for non-critical hygiene applications, such as CIP initial rinses. Integration within process here is the use of RO plant after the initial and second rinse to treat the water and reuse the RO water permeate (see Figure 6-8).

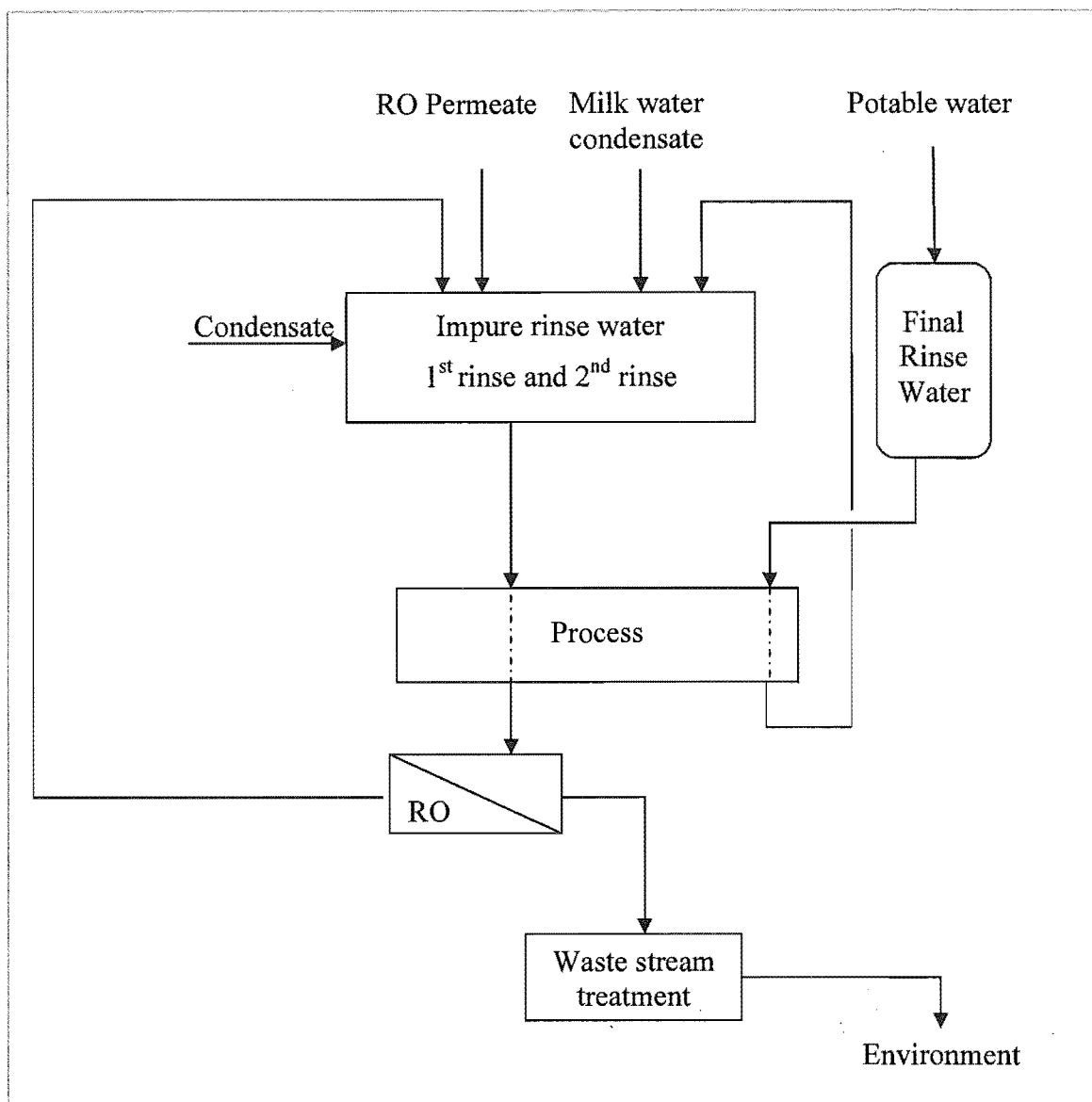


Figure 6-8 Minimal discharge CIP

6.3.6 Environmental Integration

Environmental integration is a very important topic and needs to be considered at an early stage of the design. Waste pollutants from the plant must be disposed of in an acceptable manner and as minimum as possible. Therefore some form of treatments, e.g., separation, purification, cooling may be necessary prior to disposal.

The interest in waste minimisation comes from two aspects. One of them is the economic incentive of increasing product yield through dairy process efficiency. Another is the reduction of the environmental impact of the dairy industry, together with waste treatment and disposal costs.

Each step in milk processing provides an opportunity for waste to be released. Therefore, the application area of environmental integration in the dairy process industry is very important. Furthermore, the dairy industry in many countries is pasture based and has a low cost structure compared to the dairy farming in other countries where the dairy industry is based not only on pasture but also on grains. The role of soil health is extremely important to maintain milk production. One must maintain pasture or grain production which relies on the condition of the soil.

Land farming can replace conventional biological treatment systems to minimise the biodegradable oxygen demand (BOD) in some cases. Treated industrial waste waters can be applied directly to land in various irrigation schemes.

Most of the waste minimisation studies in the open literature focus on continuous plant. Research work dealing with the design of environmentally benign batch/semi-continuous plants, which are extensively used in food industries, is rather limited (Stefanis *et al.*, 1997). The conceptual design methodology considers environmental integration in the conceptual design methodology by minimising waste generation in dairy processing. A minimal adverse environmental effect requires environmental integration.

6.3.6.1 Emissions Control for Good Process Design

Emissions should be controlled by optimum process design so that emissions are minimised. For milk processing, the simplest way to determine emissions is by measuring the effluent streams from all sources. The design for environment should fit within an integrated product process by waste minimisation (Arthur D. Little, Inc., 2001).

The losses of milk components in the streams require consideration and for that an extra rule may be considered:

1. If the losses are less than about 1% of feed by value, they would become effluent.
2. If the losses are more than about 2% of feed, then they would need to be recovered at least for stock food.

6.4 Dairy Requirements and Limitations on Process Integration

The dairy process industry has specific requirements and limitations on product integration that have to be considered prior to developing process integration. Limitations imposed on processes due to product safety, functionality, economics and environment are cited as in the following:

Product safety and processing requirements are:

1. Product must be traceable.
2. Pathogen control cannot be bypassed.
3. There are limitations on recycling water or products because of the potential for microbial cross-contamination of product.
4. Excessive pumping will damage the fat globules and proteins can be denatured.

6.4.1 Differences from Petrochemical Methodologies

Process integration is widely used in the petrochemical industries, but in the dairy industry it is just starting to take on more importance. Process integration in the petrochemical industries was established as good practice a long time ago. In the dairy industry the concept is just being introduced.

The methodologies applied in the petrochemical industries start with energy integration, while in the dairy industry the starting point was effluent minimisation, with an attempt to minimise the biodegradable oxygen demand (BOD). The raw material, milk, has some special features that distinguish it from other feed materials, especially the petrochemical materials. Some components of the milk are heat and shear sensitive, so processing conditions are limited (see Section 3.5).

Chemical engineers seek to make petrochemical processes continuous, but the dairy industry is constrained by the need to clean the processing equipment. Some processes are identified by their batch nature, e.g., milk storage in a silo, cheese making and ion-exchange while any continuous processes, such as evaporation, seldom continue for more than 20 hours before cleaning is required. A single exception is spray drying of milk with a single dryer fed by multiple evaporator that can operate for perhaps a month continuously before cleaning is required.

Significant differences exist between a petrochemical and a dairy processing operation. Dairy process streams contain significant amounts of water. Control of microbial growth and contamination (product safety) are paramount. Storage time and buffering between processes is therefore limited. Essentially, all liquid processes must stop every few hours for cleaning, in order to control microbial growth. Regular stoppage and limitations on intermediate storage make the process integration a challenging task.

Process streams are generally heat labile, so many operations are carried out with minimal thermal processing. Extensive heat recovery is used within the thermal processing operations (e.g., multiple effect evaporators with vapour recompression), but many other processes do not operate at elevated temperatures. Thus, little opportunity exists for heat integration between processes.

The processing time in the dairy industry is a concern for time integration. For example, the amount of fouling deposit always increases with time. Fouling in the dairy industry is more severe than that in other industries. In the petrochemical industry, it is common to clean only once a year or less but in the dairy industry it is necessary to clean the processing plant after a few hours of operation (see Section 3.6).

6.4.2 Similarities to Petrochemical Methodologies

Although there are significant differences between petrochemical and dairy processing operations, as described in Section 3.1, some of the petrochemical processing ideas are still applicable to the dairy process as well as dairy process integration.

Large dairy plant sites are becoming increasingly similar to petrochemical industry installations. Large scale dairy plants operate 24 hours and seven days. The aims of process integration are similar, like heat integration, loss minimisation and minimised effluent production.

Large dairy processes are integrating and fractionating their products in more specific components such as fat fractionation (see Section 5.4.4).

Factory automation for process integration is another similarity. Large dairy plants are using programmable logic controllers (PLC) in their operation similar to petrochemical plants. Automation increase the ease integration within or between processes.

The energy recovery and reusing utilities are becoming more sophisticated in the dairy industry as they do in the petrochemical industry. Energy minimisation at a dairy processing site as well as petrochemical processing may require process integration within and between process units.

6.5 Effect of Scale on Economics of Integration

There are key point opportunities for integration and these depend on:

1. The product mix. The large scale dairy industry site will probably produce a diverse range of products. These large sites have increased opportunity for integration between processes. In contrast, a small scale dairy industry site produces fewer product types. Consequently, there are reduced opportunities for between process integration.
2. The cost of integration. A number of options for process integration require additional process plants, e.g., a RO plant or UF plant. The economics of those processes are typically dependent on scale. The economic viability of integration is usually greatest on large scale sites.
3. Utilities and effluent production. Large processing sites are typically subject to restrictions on water uptake and effluent production.
4. Process integration offers a viable means to achieve capacity increases without increasing water supply or effluent discharge requirement.
5. Small scale operations may be able to gain approval for increased water supply or effluent discharge at a lower cost, making this approach more desirable than employing integration techniques.
6. Product losses. On a large scale dairy site, the cost of product losses became sufficiently high to justify sophisticated recovery systems. These systems provide additional opportunities for process integration. On a large scale, product losses may also incur additional effluent treatment costs. The combined cost of lost

product and effluent treatment may make product recovery systems economically viable.

6.5.1 Small Scale Dairy Process Industry

Small scale processing is often the most viable, if not the only, option available for successful and profitable liquid milk processing in many situations with a poorly developed or emerging dairy industry. Even though small scale processing seems to be inevitable, its operations may not always be easy. It is important to highlight the technical and economic challenges that developing countries face as chemical engineers try to promote small scale processing in the most integrated way possible.

The dairy process industry has been appropriate for developing countries, where agricultural products are the basis of existence for the population, and milk is sometimes the only exchangeable fresh good because of its known nutritive value and daily use.

As long as a dairy process takes place on such a small scale basis, it enjoys relatively high independence, a local market, and low economic risks. Simple economic structures still function using local resources as well as locally made equipment, and local customs and traditions are respected (Homewood, 1986).

Small-scale plant dairy industries process milk from a single cow to about 250 cows at the peak, using unit operations and the product alternatives described in Chapter 4 and Chapter 5 respectively. In this work, small scale processing refers to those unit operations handling more than 10 litres but less than 5000 litres of milk per day.

In the late 1970s and early 1980s, dairy industries with 500 litres of milk per day or over were essentially “block mounted”, with turn-key projects of 500 litres per hour capacity (up to 5,000 per 8 hour shift). From the author’s experience in Peru, the operations of these small plants were in most cases not very successful. In some cases, even these “small scale” industries would be still too large for the small volumes of locally produced milk (often less than 2000 litres per day) that could be made available. For someone in New Zealand or Europe it may sound inconceivable that local milk producers in Cusco-Peru cannot produce enough milk to satisfy the requirements of such a small plant. The reasons are varied, but some of the very common ones are:

1. The plant is located in a town far away from the rural based milk producers where road networks are so bad that is uneconomical for the processor or milk producers to transport the milk to the plant, particularly during the wet season.
2. The milk marketing system is highly unregulated with informal milk traders offering a cheaper product to (mostly poor) consumers in the form of raw milk which they boil at home anyway. The informal milk marketing of raw milk accounts for more than 90% of milk marketed.
3. The majority of low income earners in urban centres cannot afford the added cost of pasteurised milk, especially when expensive packaging systems are used, e.g., evaporated canned milk which has a higher cost than raw milk.
4. The high cost of processing due to inadequate plant capacity utilisation, high electricity tariffs, and taxes on processed milk versus no tax on raw milk.

Besides the technological advances that have been made in the dairy industry and the subsequent drive for larger and more efficient plants in developed countries, the concept and need for a design methodology for small scale milk processing remains as valid and relevant today in most countries with a developing dairy industry as it was 100 years ago, when developed countries served the needs of the on-farm producer-processors.

6.5.2 Medium and Large Scale Dairy Process Industry

Medium scale dairy processing in this thesis considers the production of milk from more than 250 to 25,000 cows, which may produce approximately 5,000 to 500,000 l/day. Whereas, large scale refers to milk production above 500,000 l/day at the peak.

Dairy industries in many countries have commenced reducing manufacturing costs through the amalgamation of small companies and the more efficient processing of large volumes of milk in a relatively few, centralised processing sites (Vickers, 1979).

The growth of milk production forces the dairy industry to increase its operations capacity and energy supply as well. This provides the opportunity for the discharge of contaminants to air from dairy production that can be mitigated, reducing negative impacts by minimisation of steam usage by process integration. This has been well used in other industries such as the petrochemical industry.

There is an increasing demand on steam supply in the area of the manufacturing plant at a time of increasing production. To prevent this becoming a major problem in the dairy industry, it is necessary to consider techniques and design methods to use the energy efficiently (Quispe-Chávez *et al.*, 2001). Process integration offers possibilities for reducing the steam demand as production levels expand.

The benefits include that the operating cost will be reduced by waste minimisation. Monitoring the performance during process integration will aid identifying environmental issues associated with the expansion, since the need to work under regulatory conditions is of paramount importance to the dairy industry.

Noise levels, powder emissions in the exhaust drying air from large spray driers and stack emissions from large coal fired boilers have become a source of significant air pollution. Increased product and effluent spillage over longer production hours result in major effluent disposal problems (Quispe-Chávez *et al.*, 2001). Process integration would be an elegant solution to reduce emissions from coal combustion boiler equipment, and dryers.

7 Conceptual Design Methodology of Dairy Processes

7.1 Introduction

Petrochemical engineering typically uses reactions to transform the selected feedstock into the final product. Consequently, the flowsheet methodologies (e.g., Douglas, 1988) usually focus principally on the reactor. There may be several routes to the product, based on different chemical feedstocks. In contrast, dairy processing is predominantly a sequence of separations and blending, with reactions used for a small number of products. Feedstock selection is not an issue in dairy processing since all processing begins from raw milk. Consequently, any dairy flowsheeting methodology does not include feedstock selection, nor does it typically require selection of reaction pathways. Flowsheet development primarily focuses on the selection of compatible or synergistic products (i.e. process integration) as well as the selection of the most suitable order and type of separation operations. Product synergies enable the processing of by-product streams into additional saleable products of value. These synergies may be so strong or clearly defined that these by-product streams are considered to be co-products, e.g. cheese and whey protein concentrate (WPC) production. WPC is typically considered to be a co-product of cheese manufacture due to the high value of WPC relative to cheese, and the large costs of whey (effluent) disposal. However, it is important to review and challenge conventional dairy process design thinking for several reasons:

- 1) The development of new processing (especially separation) technologies, which provide new alternatives for product integration, or provide alternative means to manufacture products, allow different integration (and co-product) options.
- 2) Flowsheeting heuristics relating to process integration and co-product production may well be strongly scale dependent. The development of an overall flowsheeting methodology should provide a technique to consistently identify the best flowsheeting options for any scale of operation.

- 3) Systematic flowsheet development provides the opportunity to identify new product opportunities, e.g., recovery of valuable components from waste streams, or new opportunities to manufacture existing products by more efficient or lower cost methods.

7.2 Conceptual Design Methodology of Dairy Processing

In this chapter, a methodology for the synthesis of dairy process flowsheets is presented.

The feasibility of dairy process flowsheet integration will be strongly dependent on scale (see Section 6.5), e.g., smaller scales will favour single product operations, with fewer options for integration, heat recovery and waste minimisation.

Any process design for new processes goes through at least three stages. One is the conceptual design with the generation of ideas for new processes (process synthesis) and their translation into an initial design. This stage includes preliminary cost estimates to assess the potential profitability of the process, as well as analysis of process safety and environmental considerations. The second stage is the final design where a rigorous set of design calculations to specify all the significant details of a process is performed. The final stage involves detailed design including the preparation of engineering drawings and the equipment list needed for construction (National Research Council *et al.*, 1988). The use of methodology is the norm for conceptual process design, that provides insights. When it is combined with numerical methods, it creates innovative but practical design tools which are tomorrow's contribution to a powerful working environment for conceptual process design (Linnhoff *et al.*, 1994).

Four case studies have been developed to illustrate the application of process integration using the dairy operations presented in Chapter 4 and dairy products in Chapter 5. The aim is to present and demonstrate a method for matching streams for integration within and between units in a process flowsheet.

Tools for the design methodology synthesis

This methodology will create “partial process flowsheets” that can be joined together later to form a complete process. This avoids the need to carry numerous different combinations all through.

It is necessary, for the proposed design methodology, to designate a code to each process operation, product, and a code for the utilities as follows. The numbering conventions are established in Tables 7-1, 7-2, and 7-3. These are for utilities, unit operations, and products and key process operations respectively.

Table 7-1 Designation codes of utilities (to label process flowsheets).

	Utility	Code
Energy	Steam	st
	Electricity	el
Water	Potable water	pw
	Hot water	hw
	Cooling water	cw
	Chilled water	iw
	Milk water condensate	mw
	Demineralised water	dw
Air	Hot air	ha
	Cool air	ca
	Moist air	ma

Table 7-2 Designation codes of unit operations (to label process flowsheets).

Process operation	Process code	Process feed	Process products	Product is concentrated liquid	Up to TS %
Microfiltration (loose)	MF _a	Liquid	Liquid	Yes	10
Microfiltration (tight)	MF _b			Yes	13
Ultrafiltration	UF			Yes	30
Nanofiltration	NF			Yes	25
Reverse osmosis	RO			Yes	21
Electrodialysis	ED			No	
Dialysis	DI			No	
Evaporation	E			Yes	50
Ion Exchange	IX			No	
Homogenisation	HG			No	
Spray drier	SD		Solid	No	
Roller drier	RD			No	
Freeze drier	FD			No	
Centrifugal separation	SP	Liquid or Solid-liquid	Liquid and liquid/or solid	No	
Screen filtration	SF	Solid-liquid	Solid or slurry and liquid	Yes	
Fluidised bed drier	FB	Solid	Solid	No	
Dry blending	DB			No	
Precipitation	PT	Liquid	Solid	No	
Crystallisation	CR	Conc. liquid	Crystals	No	
Wet blending	WB	Solid-liquid or liquid-liquid	Liquid or slurry	Yes	50
Pathogen control	PC	Solid, liquid or slurry	Solid, liquid or slurry	No	
Storage	ST			No	
Packing	P			No	

7.2.1 Key Process Operation

Generation of flowsheet alternatives can be very daunting given the large number of possible combinations. In the dairy industry there is a key process operation that cannot normally be avoided in processing any product. A key process is a very important concept. It provides a mean to simplify the problem by first focusing on developing flowsheet options downstream process, and once this is achieved upstream flowsheet options are developed. Where there is more than one operation involved, the unique operation required to achieve the final product is the key process operation.

The key process operation of most of the different products as discussed in Chapter 5 is shown in Table 7-3.

**Table 7-3 Designation codes of products and key process operations
(to label a product flowsheets).**

Products	Product Code	Key process operation	Key process operation code	Common processes
Fat or cream	<i>CR</i>	Centrifugal separation	SP	PC
Water	<i>W</i>			
Skim liquid milk	<i>SM</i>			
Whey protein	<i>WP</i>	Casein Precipitation	PT	
Cheese	<i>CH</i>	Reaction & Precipitation	RE & PT	
Yoghurt	<i>YO</i>	Reaction	RE	
Sour cream	<i>SC</i>			
Ethanol	<i>OH</i>			
Butter milk	<i>BM</i>	Phase change	PHC	
Butter	<i>BT</i>			
Anhydrous milk fat	<i>AMF</i>			
Milk-fat based spreads	<i>MFS</i>			
Fractionated fats	<i>FF</i>			
Dry lactose	<i>LC</i>	Crystallisation	CR	
Casein protein	<i>CS</i>	Precipitation	PT	
Minerals	<i>M</i>			
Skim milk powder	<i>SMP</i>	Spray drying	SD	
Instant skim milk powder	<i>ISMP</i>			
Whole milk powder	<i>WMP</i>			
Agglomerate whole milk powder	<i>AWMP</i>			
Butter milk powder	<i>BMP</i>			
Milk protein concentrate	<i>MPC</i>			
Caseinate powder	<i>CSTP</i>			
Whey powder	<i>WP</i>			
Cheese powder	<i>CHP</i>			
Baby powder	<i>BP</i>			
Whey protein concentrate	<i>WPC</i>			
Whole liquid milk	<i>WM</i>	None	None	

PC = Pathogen control

7.3 Dairy Process Design Methodology

The methodology presented below was developed by rigorously analysing the steps taken during the design of a complete dairy process flowsheet. It formalises the steps that an experienced designer might follow, while at the same time it provides a framework for innovation.

The methodology has been formulated so that it is applicable to any scale of operation. It has been written in such a way that it could be implemented using a computer program to aid the storage of the different possible process flowsheet options. It is very likely that its application will not be limited to the dairy industry.

In this methodology the term “process” refers to the overall process from raw milk feed to final saleable product. The term “operation” or “process operation” is used to identify a single unit operation within the process. Within the methodology, the term “flowsheet” is used to identify the incomplete process that has been synthesised at any particular stage.

This methodology can be applied by the process designer to the process of interest during the conceptual design stage without the need for rigorous modelling and calculations. The methodology described here is used to generate the guidelines and the conditions for their use.

During the design methodology, it is advised to keep a track of the thoughts. Thoughts must be written as carefully as possible during the whole design process cycle as they appear.

The design procedure can be expressed as a flowchart as shown in Figure 7-1.

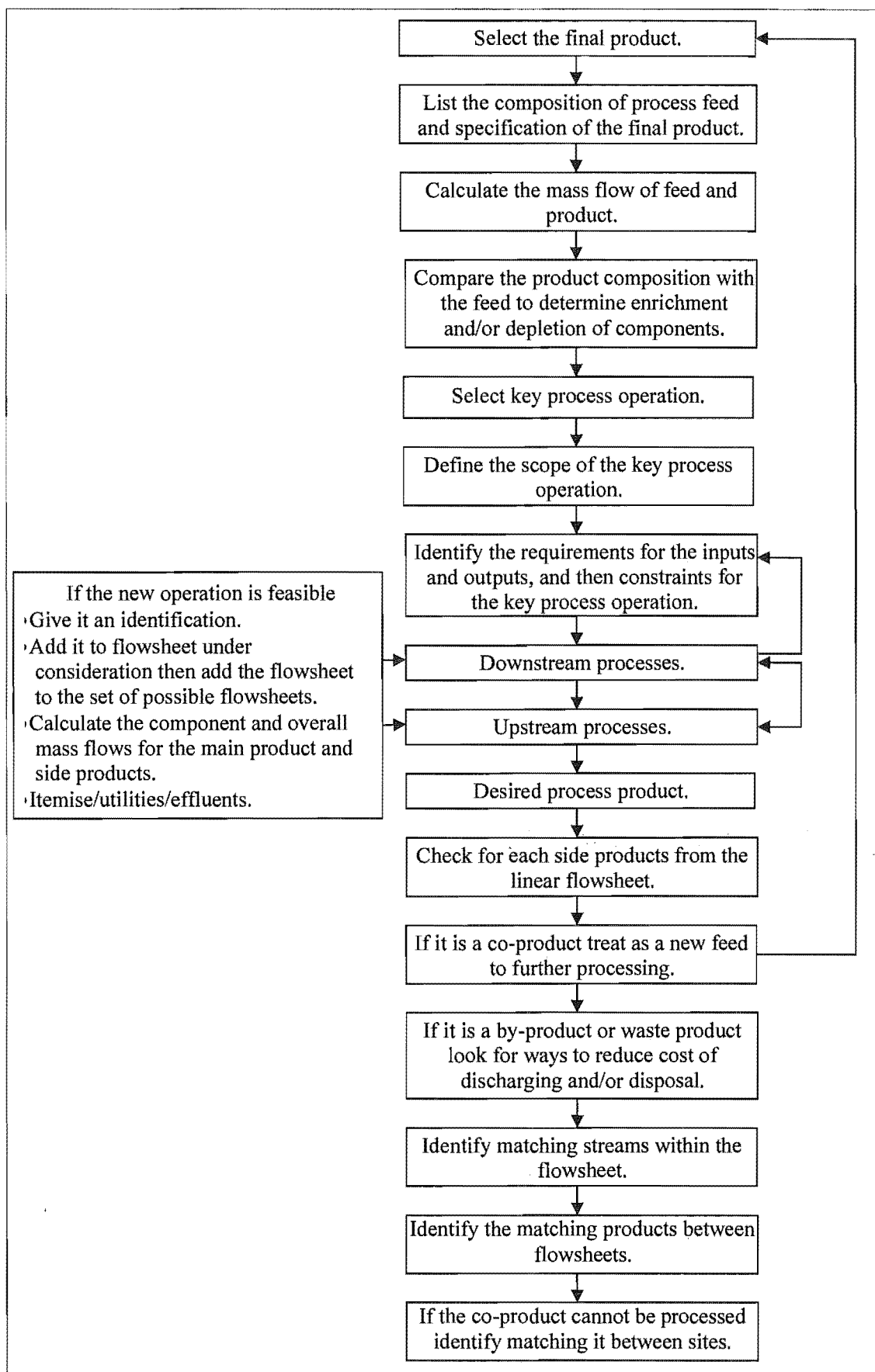


Figure 7-1 Proposed synthesis design methodology flowchart.

The dairy process methodology incorporated here is based around the key process operation with integration. The steps in dairy process methodology are as follows:

Step 1: Select the final product.

Step 2: List the composition of process feed and specifications of the final product.

Step 3: Calculate the mass flow of feed and product (see Section 4.9.2).

Step 4: Compare the product composition with the feed to determine enrichment and/or depletion of components.

Step 5: Select the key process operation from Table 7-3 (based on Chapters 4 and 5).

Step 6: Define the scope of the key process operation from the feed to its product and relate the operation feed and product to the overall process feed and product. Designate a letter from Table 7-2 to the process.

Estimate the capital cost of the flowsheet and check its economic viability.

Step 7: Identify the requirements for the inputs, outputs and constraints of the selected key process operation (see Chapters 4 and 5). For the inputs, include composition calculations by approximate mass balance.

Step 8: Downstream processes:

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the last operation in the flowsheet does not produce the overall process product:

Find all operations that can process feeds the same as the current flowsheet product. For each of these:

If the new operation is feasible:

- Give it an identification.
- Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.

- Calculate the component and overall mass flows for the main product and side products.
- Itemise utilities/effluents/timing.
- Estimate the capital cost of the flowsheet and check its economic viability.
- Call this step recursively.

Step 9: Upstream processes:

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the first operation in the flowsheet is not fed by the overall process feed:

Find all operations that can produce the feed for the current flowsheet.

For each of these:

If the new operation is feasible:

- Give it an identification.
- Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.
- Calculate the component and overall mass flows for the main product and side products.
- Itemise utilities/effluents/timing.
- Estimate the capital cost of the flowsheet and check its economic viability.
- Call this step recursively.

A linear flowsheet is now designed. The linear process flowsheet may produce certain utilities which can be integrated into the existing process flowsheet. There are perhaps co-products that can be considered to be further processed, or required ingredients to be blended into process operations. There may also be utilities required and utilities produced to process those potential co-products. Therefore continue with Step 10.

Step 10: Check for each side products from the linear flowsheet. Classify them as co-products, by-products and waste products (see Section 3.3).

Step 11: If it is a co-product, treat it as a new feed to the further processing and repeat the design methodology from Step 1.

Step 12: If it is a by-product or waste product, look for opportunities to off-set cost of discharging otherwise determine a suitable treatment for its disposal.

The new process flowsheet corresponds to an integration problem with a parallel flowsheet.

Step 13: Identify the matching streams *within the flowsheet*. Consider products and equipment constraints. Check for energy, water, time and environmental integration opportunities.

Step 14: Identify the matching products *between flowsheets (linear flowsheet and the new co-product processing flowsheets)*. Check for energy, water, time and environmental integration opportunities.

Step 15: If the co-product cannot be processed due to the capacity problem, it may be necessary to identify the proximity matching product *between sites*.

This methodology will produce a well integrated process flowsheet producing the product and possible co-product, by-product and treated effluent.

7.4 Dairy Process Design Methodology Case Studies

Four case studies are presented to illustrate the use of conceptual methodology for the design of dairy processes. The first case study is a “very small” scale dairy process and is followed by a “small” scale process case study (case study 2). The third case study involves the medium scale dairy process, and then a large scale dairy process is presented in case study 4. Each case study highlights specific aspects of the dairy process design at different production scales. The aim is to show that the methodology is capable of generating a feasible flowsheet for efficient use for both simple to complex dairy processing systems.

In the case studies the options are not all presented in the order that they would be generated by strictly following Steps 8 and 9. They are presented in a more compact manner.

7.4.1 Small Scale Milk Processing

Overview

On a small scale, some specific factors need to be considered, such as location of the plant, farmers’ knowledge and market traditions. The consideration of these factors is important, for what may be small scale in one country could be medium or large scale in another, depending on the level of development. Each factor has a large influence on the choice of products, unit operations, technology and utilities that may be available.

Liquid milk occupies a dominant position in milk processing, marketing and consumption in small scale milk production. This is because it is a basic food in many societies where cattle and other milk producing animals form an important part of the agricultural production system. The form in which the milk is presented for sale ranges from on-farm and market raw milk sales in most of the developing countries to pasteurised or UHT milk in countries with developed dairy industries. If one reviewed the history of dairying in most of the European, North American and Australasian countries, one would see the quantity of liquid milk products in the dairy industry increasing over time in proportion to the level of economic and technological development in those societies. Consumers in richer societies demand and consume a more diversified mix of milk and milk products.

The selection of liquid whole milk as a product of small scale farms in developing countries has many advantages and few requirements:

- No need for cooling. Milk product is immediately consumed.
- No need for separation. Milk is usually used as whole liquid milk.
- Need for pathogen control. Although, liquid milk product is consumed soon after milking, the pathogen control is achieved when the purchaser boils it.
- No cheese production. This is rare, since there is no leftover liquid milk.
- No need for packaging. Product is directly delivered into the customers' containers.
- No need for marketing. Each producer has its own clientele.
- No need for transport/delivery. The market is in the vicinity.

In a small scale and a short time batch operation there are usually limited resources available to develop the processes. Table 7-4 shows the different process alternatives to assist small scale milk production.

Table 7-4 Processes for small scale milk production.

Process	Alternatives
Pathogen control	Batch heating
Cream separation	Natural separation
Curd precipitation	Addition of calf rennet (calf stomachs)
Process integration	Animal feed, land field irrigation

Small scale dairy processing has almost no cost involved assuming that the farmer has the basic utilities within a normal domestic kitchen. Similarly, labour is cheap or involves no cost at all.

Some small scale product options are shown in Table 7-5.

Table 7-5 Product alternatives for a small scale milk production.

Options	Products	Co-product
Fresh products	Liquid whole milk	None
	Liquid skim milk	Cream
	Cultured milks	None
	Butter	Skim milk & butter milk
	Cottage cheese	Whey
“Dried” products	Salted cheese	Whey
	Unsalted cheese	Whey

7.4.1.1 Case Study One: Very Small Scale Milk Processing (Whole Liquid Milk)

Overview

Household technologies are important for household food security and traditional processing of milk. Case study one refers to a very small scale of dairy product processing. The processing of raw milk from one to a hundred cows is considered. Factors such as the lack of electricity and poor road conditions for marketing and distribution of milk are characteristic of very small scale dairy processes.

Design Methodology

Step 1: *Select the final product.*

Product = Whole liquid milk

Step 2: *List the composition of process feed and specifications of the final product.*

Feed = 100 kg per day of raw liquid milk (for typical composition see Table 5-1).

Product specification: The product needs to be clean and safe to drink in a few hours (less than 24 hours) after it is purchased.

Step 3: *Calculate the mass flow of feed and product.*

The capacity is calculated on a wet basis:

Mass flow of feed = 100 kg per day of whole liquid milk.

Since there is no cream separation:

Mass flow of product = Mass flow of feed

If one day = 8 production hours,

Mass flow of product = 12.5 kg hr^{-1} of whole liquid milk

Step 4: *Compare the product composition with the feed to determine enrichment and/or depletion of components.*

In a small scale situation, this step can be avoided because raw milk components will remain unchanged in the process.

Step 5: *Select key process operation from Table 7-3 (based on Chapters 4 and 5).*

From Table 7-3 (based on Section 4.1.4), pathogen control is the general process required. In a domestic situation the boiling of milk will ensure pathogen control.

Step 6: *Define the scope of the key process operation from the feed to its product and relate the operation feed and product to the overall process feed and product.*

Designate a letter from Table 7-2 to the process.

Estimate the capital cost of the flowsheet and check its economic viability.

The scope of the process is straightforward. The raw milk is collected, boiled and delivered to the customer. Figure 7-2 shows the flow sheet of pathogen controlled whole milk.

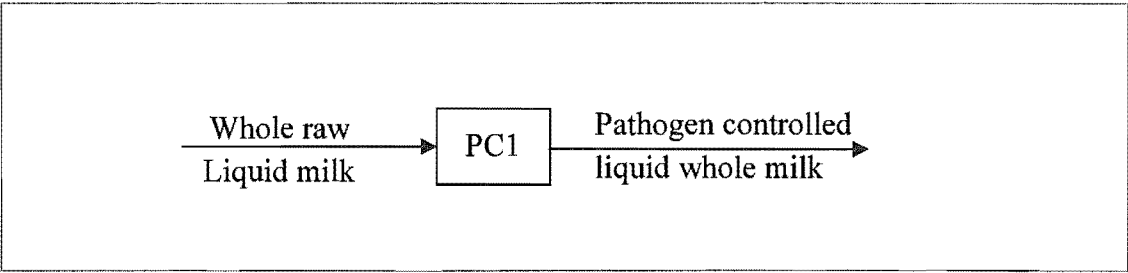


Figure 7-2 Whole milk process flow sheet.

Step 7: *Identify the requirements for the inputs, outputs and constraints of the selected key process operation (see Chapters 4 and 5). For the inputs, include composition calculations by approximate mass balance.*

The input and output have already been described in Step 2.

Utilities required are heat to boil the milk, water and detergent for cleaning.

Step 8: *Downstream processes:*

Downstream processes are not required since pathogen control produce the desired product.

Table 7-6 from Section 6.5.1. summarises process alternatives for a very small scale processing of raw whole liquid milk.

Table 7-6 Summary of process alternatives.

Process option	Process operation	Option	Comments
Option 1	SP	X	Milk is usually used as whole liquid milk with the expectation that a cream layer forms on top.
Option 2	HG	X	Not required by the customer.
Option 3	P	X	Product is directly delivered to the client's container.
Option 4	ST	X	There is no excess milk to be stored.

In this case study, pathogen control produces the final product.

Step 9: Upstream processes:

Upstream processes are not required since pathogen control produce the desired product.

Step 10: *Check for each side products from the linear flowsheet. Classify them as co-products, by products and waste products (see Section 3.3).*

For this linear flowsheet there is neither co-product nor by-product. The side products only consist of cleaning wastes.

7.4.1.2 Case Study Two: Small Scale Milk Processing (Packed Cottage Cheese)

Overview

Small scale dairy processing considered here handles up to 5000 kg of milk per day. The process method should be tailored to the use of local raw materials, local manpower and energy sources whenever possible. If a technology is to be used, it has to be adapted to the people using it. These matters need to be considered in conjunction with the economical viability.

While small scale processing remains inevitable in developing countries, a design methodology for a scale below 5000 kg of milk per day does not appear to be available in the open literature. This case study demonstrates that flowsheet alternatives are dependent on the scale of operation.

Design Methodology

Step 1: *Select the final product*

The choice of product is selected based on the market demand. The product studied as an example here is packed cottage cheese.

Step 2: *List the composition of process feed and the specification of the final product*

Feed = 5000 kg raw whole milk per day

The composition of feed, product composition and specification are listed in Table 7-7.

Table 7-7 Composition of milk feed and cottage cheese product (based on Spreer, 1998 and Kessler, 1981).

Components	Composition of feed [% w/w]		Composition of product [% w/w]		Specification [% w/w]
	Wet basis	Dry basis	Wet basis	Dry basis	Wet basis
Fat	3.90	30.7	4.3	19.5	4.3 ± 1
Casein protein	2.60	20.5	12.3	55.9	} 12.8
Whey protein	0.65	5.1	0.5	2.3	
Lactose	4.60	36.2	2.0	9.0	
Minerals and miscellaneous	0.95	7.5	1	4.5	
Salt	0.0	0.0	1.9	8.6	1.9
Water	87.30	0.0	78	0.0	78
Total solids	12.70		22		

Additional product specification include producing fresh cheese with a shelf life of not less than 4 weeks.

Step 3: Calculate the mass flow of feed and product

Mass flow of feed = 5000 kg raw whole milk per day

$$\text{Mass flow of product} = \frac{\left(\text{flowrate of feed} \right) \times \left(\frac{\% \text{ casein}}{\text{in feed}} \right) \times \left(\frac{\% \text{ yield of casein in process}}{\% \text{ casein in product}} \right)}{\left(\frac{\% \text{ casein}}{\text{in product}} \right)} \quad (7-1)$$

$$\text{Mass flow of product} = \frac{5000 \text{ kg/d} \times 2.6 \% \times 95 \%}{12.3 \%}$$

Mass flow of product = 1004 kg of cottage cheese per day

If 1 day = 8 production hours, then mass flow of product = 125.5 kg hr⁻¹

The component mass balance is dependent on the percentage of casein yield (95%). The spreadsheet calculation of this component mass balance is in Appendix A.

Step 4: *Compare the product composition with the feed to determine enrichment and/or depletion of components.*

Table 7-8 shows the components that need to be added and removed. Only salt needs to be added here. Details of the calculation are in Appendix A.

Table 7-8 The addition and removal of components.

Component	Enrichment [kg hr ⁻¹]	Depletion [kg hr ⁻¹]
Fat		19.0
Casein		0.8*
Whey protein		3.4
Lactose		26.2
Minerals and miscellaneous		4.7
Salt	2.4	
Water		447.7

* not zero because the casein yield of the process is 95%.

Step 5: *Select key process operation from Table 7-3 (based on Chapters 4 and 5).*

From Table 7-3 (based on Section 5.7), the key process operations for cheese are reaction and precipitation.

Step 6: *Define the scope of the key process operation from the feed to its product and relate the operation feed and product to the overall process feed and product. Designate a letter from Table 7-2 for the process.*

Estimate the capital cost of the flowsheet and check its economic viability.

The key process operations and the scope of the process are shown in Figure 7-3.

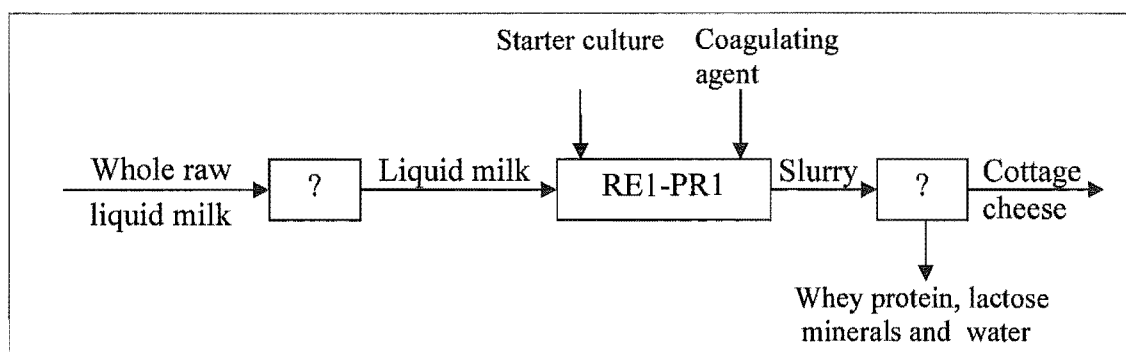


Figure 7-3 Cottage cheese process scope.

There are whey protein, lactose, minerals and water produced from cottage cheese manufacture that leave the key process as the liquid in the slurry.

The economic analysis in Appendix A shows that the key process is potentially economically viable.

Step 7. *Identify the requirements for the inputs, outputs and constraints of the selected key process operation (see Chapters 4 and 5). For the inputs, include composition calculations by approximate mass balance.*

Inputs: 1) Feed whole liquid milk with a fat content of 3.9% from Table 5.1.

2) Coagulating agent and starter culture

Outputs: 1) Product is cottage cheese slurry

Casein yield of the process is 95% (see Section 4.9.3).

Step 8: *Downstream processes:*

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the last operation in the flowsheet does not produce the overall process product:

Find all operations that can process feeds the same as the current flowsheet product. For each of these:

If the new operation is feasible:

- *Give it an identification.*

- *Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.*
- *Calculate the component and overall mass flows for the main product and side products.*
- *Itemise utilities/effluents/timing.*
- *Estimate the capital cost of the flowsheet and check its economic viability.*
- *Call this step recursively.*

From Table 7-2, there are five options that can process the product from the key process. These are shown in Table 7-9.

Table 7-9 Downstream process options for operations after the key process operation.

Process option	1 st consideration
Option 1	(RE1-PR1)-SP1
Option 2	(RE1-PR1)-SF1
Option 3	(RE1-PR1)-WB1
Option 4	(RE1-PR1)-P1
Option 5	(RE1-PR1)-ST

These process options are analysed below.

For Option 1, a centrifugal separation (SP) can remove the whey protein, lactose, minerals and water from the curd to produce cottage cheese. This is shown in Figure 7-4 as SP1. The centrifugal separator could be either a decanting centrifuge or a filter-screening (see Section 4.2.2).

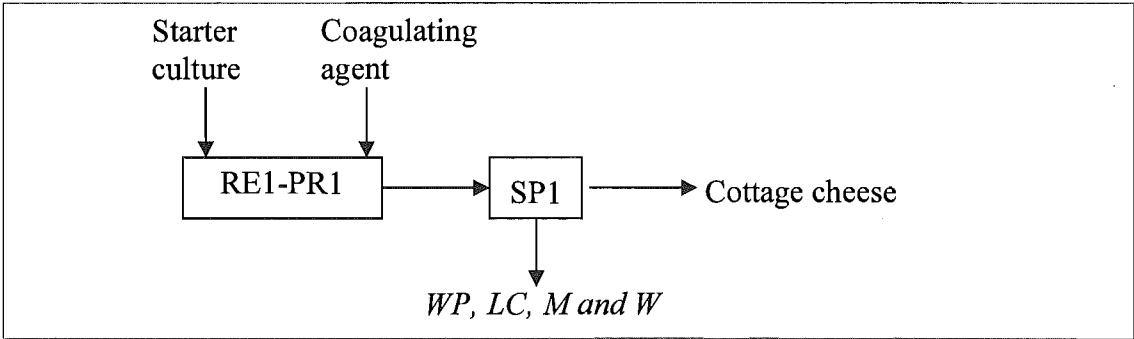


Figure 7-4 Schematic flowsheet for production of cottage cheese using centrifugal separation.

For Option 2, a screen filtration (SF) can remove the whey from the curd to produce cottage cheese. This is shown in Figure 7-5 as SF1.

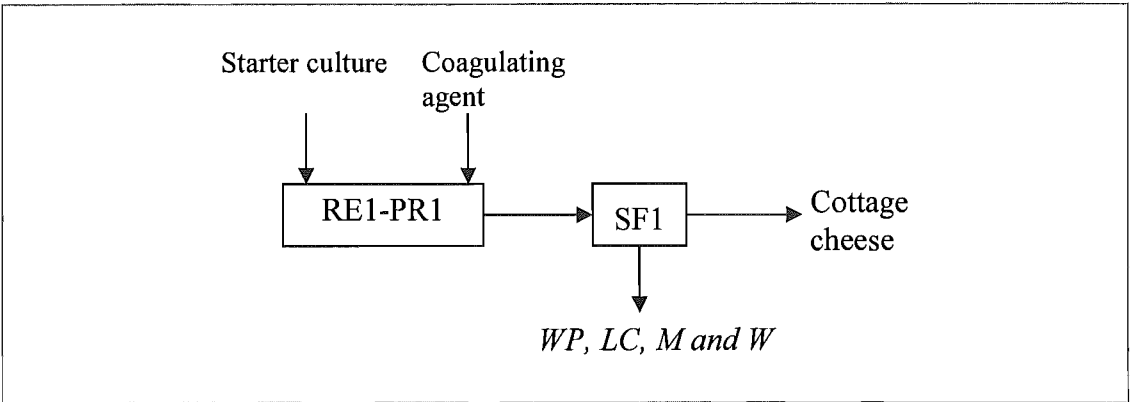


Figure 7-5 Schematic flowsheet for production of cottage cheese using screen filtration.

Option 3 uses wet blending (WB) if further components need to be added (e.g., salt) to meet the product composition. This is shown in Figure 7-6 as WB1.

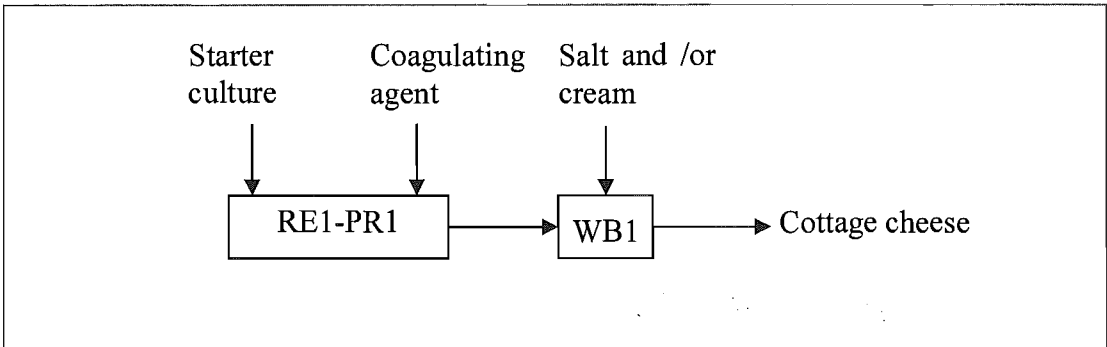


Figure 7-6 Schematic flow sheet for production of cottage cheese using wet blending.

Option 4 considers packing (P). However, the product cannot be packed directly because the product from the reaction-precipitation process has not achieved the product specifications yet.

Option 5 which considers the storage (ST) of the key process product is also rejected because there are whey proteins, lactose and minerals that need to be removed from the precipitated cottage cheese curd.

The analysis above it is shown that, out of the five options in Table 7-9, there are three processes that can process the key process product stream. These processes are SP, SF and WB. They are shown in Table 7-10 as the first consideration process options.

2nd Considerations

Table 7-10 shows the second level of downstream processes.

Downstream process options are then derived from these immediate processes. Only those marked with an asterisk (*) are considered further as examples. Processes that cannot be developed further are marked with strikethrough. Possibly feasible processes but not considered here are not marked. Less conventional alternative process options are marked with a club (♣).

Table 7-10 Possible downstream processes of the key process operation.

Process option	1 st Consideration	2 nd Consideration	3 rd Consideration
Option 1	(RE1-PR1)-SP1*	(RE1-PR1)-SP1-SF1	
		(RE1-PR1)-SP1-WB1*	(RE1-PR1)-SP1-WB1-SF1
			(RE1-PR1)-SP1-WB1-P1*
			(RE1-PR1)-SP1-WB1-ST1
		(RE1-PR1)-SP1-P1	
Option 2	(RE1-PR1)-SF1*	(RE1-PR1)-SF1-SP1	
		(RE1-PR1)-SF1-WB1*	(RE1-PR1)-SF1-WB1-SP1
			(RE1-PR1)-SF1-WB1-P1 *
			(RE1-PR1)-SF1-WB1-ST1
		(RE1-PR1)-SF1-P1	
Option 3	(RE1-PR1)-WB1*	(RE1-PR1)-WB1-SP1♣	
		(RE1-PR1)-WB1-SF1	(RE1-PR1)-WB1-SF1-SP1
			(RE1-PR1)-WB1-SF1-P1
			(RE1-PR1)-WB1-SF1-ST1
		(RE1-PR1)-WB1-P1	

For example, (RE1-PR1)-SP1 can be followed by SP1, SF1, WB1, P1 or ST1, but the first two of them are not sensible as no further separation will occur. Packing cannot yet be done as the product does not yet have the required composition. Storage does not

seems a reasonable step for a product such as cottage cheese. Blending is the only option that seems sensible. Likewise (RE1-PR1)-SF1 can only be reasonable followed by WB1. Where salt and other ingredients are added to meet the product specification (see Figure 7-7). Cream could also be added here if the fat content is too low or if the cottage cheese is precipitated from skim milk. The last of the 1st consideration, (RE1-PR1)-WB1 can only be followed by SP1 or SF1. For the 3rd consideration, packing is added to the process options flowsheet.

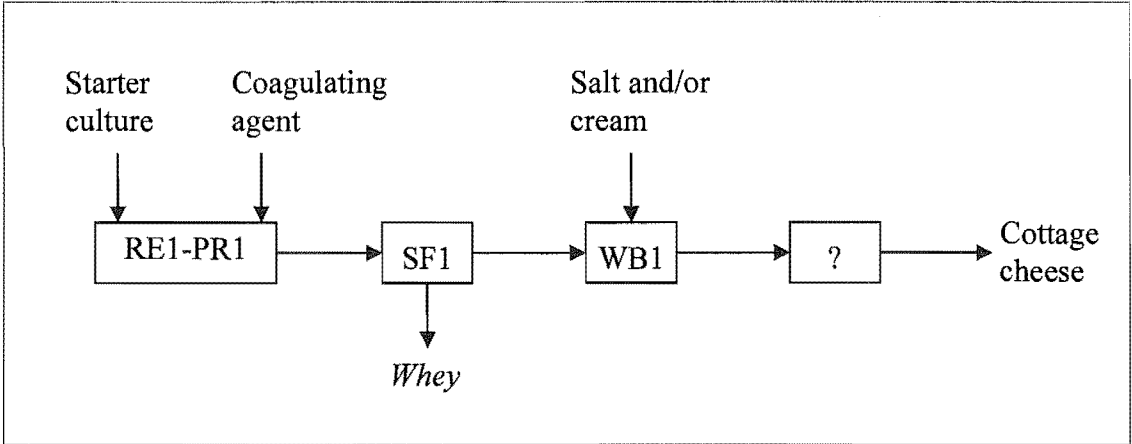


Figure 7-7 Screen filtration separation integrated with wet blending.

Once the product has achieved the product specification by centrifugal separation and wet blending, it can be packed. Therefore, packing is taken into the third list of considerations (see Figure 7-8).

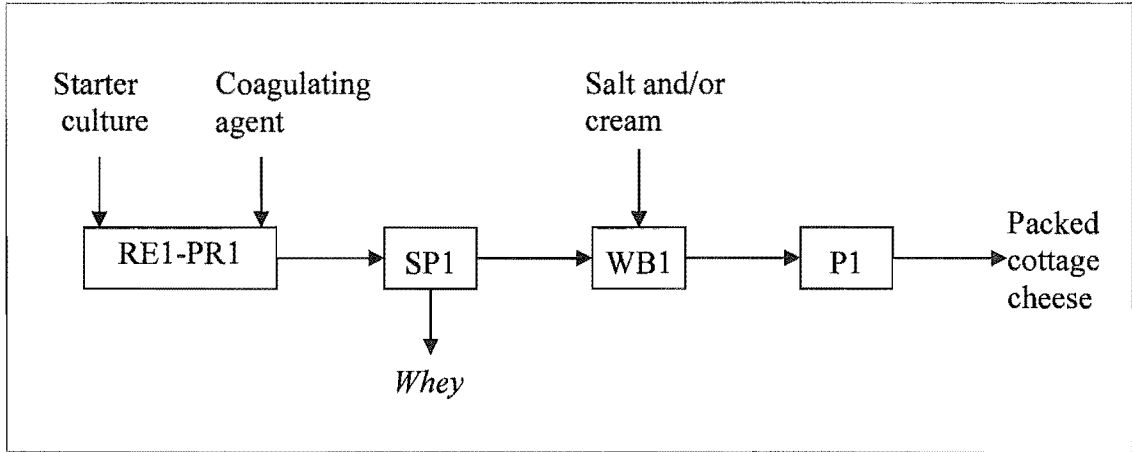


Figure 7-8 Centrifugal separation integrated with wet blending.

Once the product has achieved the product specification by screen filtration and wet blending, it can be packed. Therefore, packing is taken into the third list of considerations (see Figure 7-9).

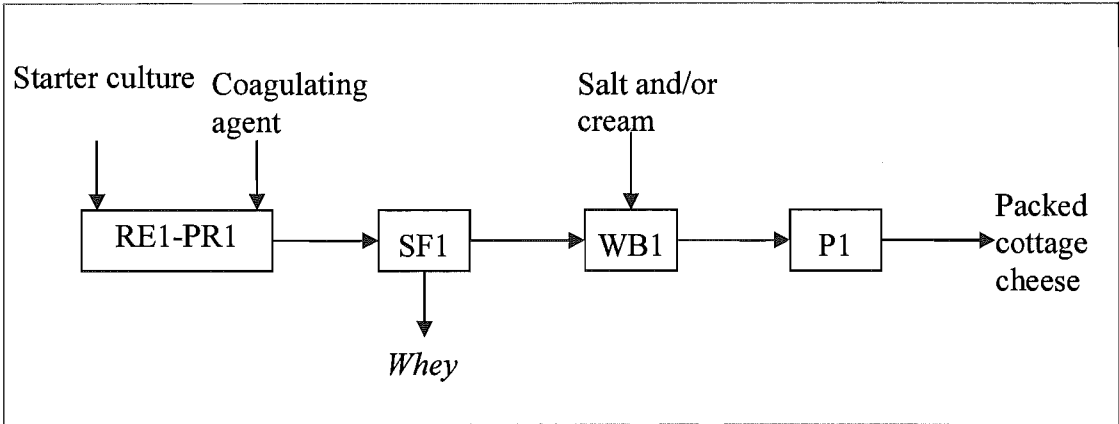


Figure 7-9 Downstream process flowsheet of cottage cheese production.

Table 7-11 shows the list of utilities and emissions downstream of the key process.

Table 7-11 Utilities and emissions for production of cottage cheese.

Code	Utilities required	Code	Emissions
st	Heating medium	ma	
hw	(80 °C; 30 °C, 26 °C)	hw	(40 °C)
cw	(4 °C)		Smell, noise
el			Wash water
pw, dw	CIP water		Cleaning agents
	Cleaning agents		

- Step 9: Upstream processes:**
- (This is a recursive step). It will potentially give many different flowsheets with a combination of operations.*
- For each current flowsheet, do the following:*
- If the first operation in the flowsheet is not fed by the overall process feed:*
- Find all operations that can produce the feed for the current flowsheet.*
- For each of these:*
- If the new operation is feasible:*

- Give it an identification.
- Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.
- Calculate the component and overall mass flows for the main product and side products.
- Itemise utilities/effluents/timing.
- Estimate the capital cost of the flowsheet and check its economic viability.
- Call this step recursively.

The process operation is fed by liquid milk. Calculations for Step 8 show that when the key process is fed by whole liquid milk, it is impossible to remove the entrapped fat downstream of the key process. This is because there is no feasible process operation in Table 7-2 to separate the fat after the casein is precipitated. Therefore, as much fat as required must be removed before the key process begins (see Figure 7-10).

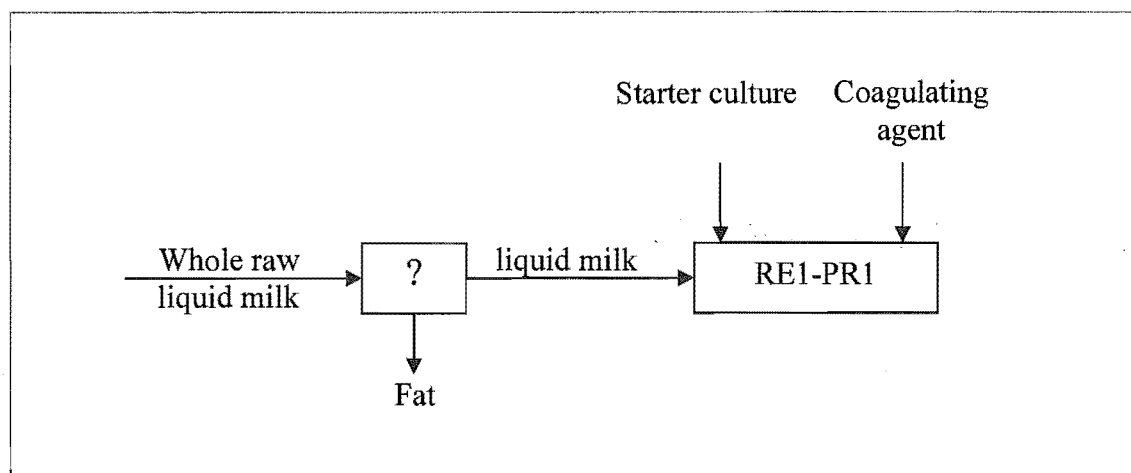


Figure 7-10 Upstream flowsheet process operation.

Various alternatives from Table 7-2 that can produce the feed to the key process are shown in Table 7-12. These options are microfiltration, ultrafiltration, nanofiltration, reverse osmosis, evaporation, centrifugal separation and pathogen control. The feed has to be liquid or solid-liquid state (Table 7-2). Only those marked with an asterisk (*) are considered further as examples. Processes that cannot be developed further are marked with strikethrough. Possibly feasible processes but not considered here are not marked. Less conventional alternative process options are marked with a club (♣).

Table 7-12 Process alternatives to feed the key process operation.

Option	1 st Consideration	2 nd Consideration	3 rd Consideration
Option 1 _a	MF _a 1-(RE1-PT1)	SP1-MF _b 1-(RE1-PT1)*	UF1-SP1-MF _b 1-(RE1-PT1)♣
Option 1 _b	MF _b 1-(RE1-PT1)*		NF1-SP1-MF _b 1-(RE1-PT1) RO1-SP1-MF _b 1-(RE1-PT1)♣ E1-SP1-MF _b 1-(RE1-PT1) PC1-SP1-MF _b 1-(RE1-PT1)
Option 2	UF1-(RE1-PT1)		
Option 3	NF1-(RE1-PT1)		
Option 4	RO1-(RE1-PT1)		
Option 5	E1-(RE1-PT1)		
Option 6	SP1-(RE1-PT1)*		PC1-SP1-(RE1-PT1)*
Option 7	WB1-(RE1-PT1)		

For Option 1_a, microfiltration can be used to remove cream and micro-organisms from casein and whey if loose MF_a membranes are used (Figure 7-11).

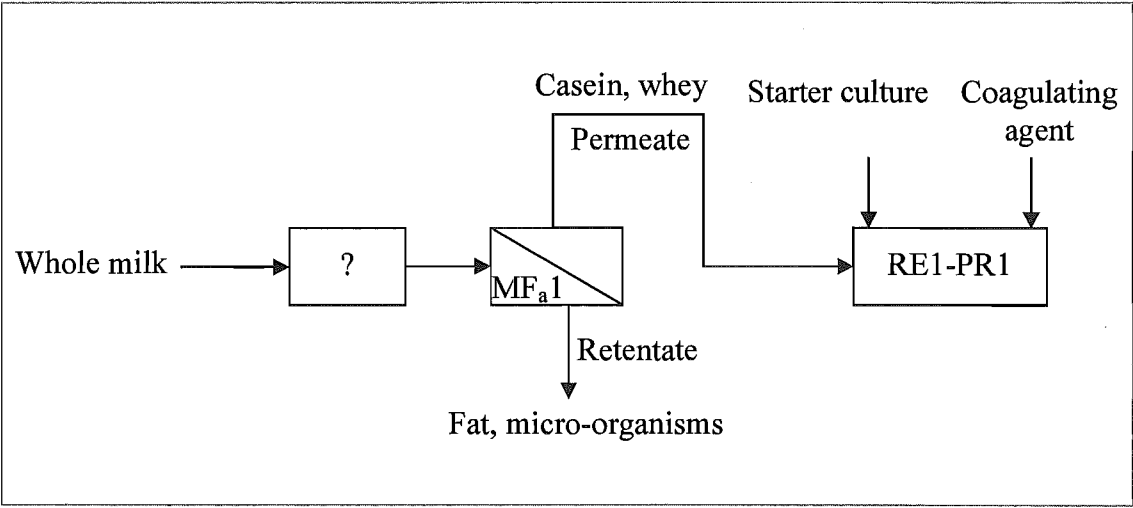


Figure 7-11 Microfiltration for pathogen control and cream separation.

For Option 1_b, casein can be separate from whey when tight MF_b membranes are used (Figure 7-12), especially in the plants that makes casein. Clearly any micro-organisms must be destroyed before this step.

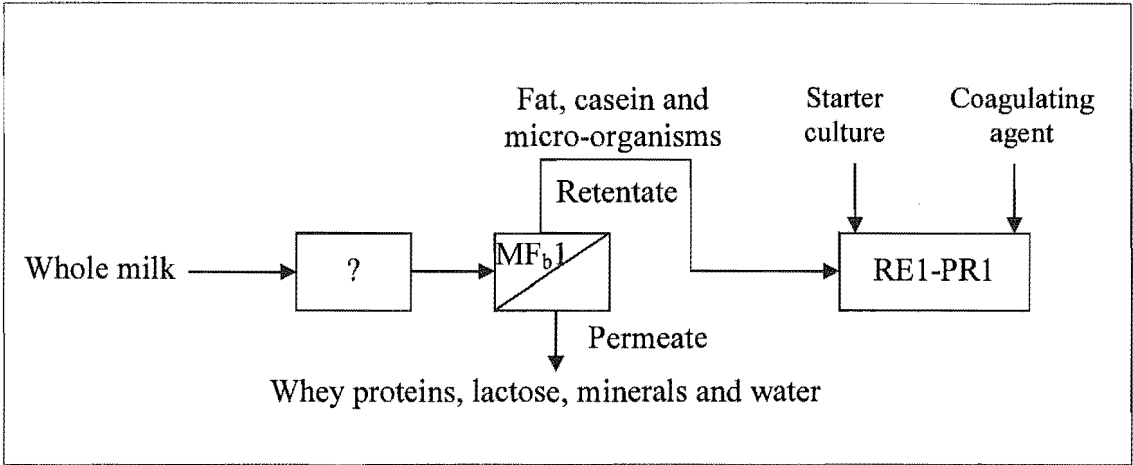


Figure 7-12 Microfiltration for casein enrichment.

For Option 2, ultrafiltration can be used to separate protein and fat from the lactose, minerals and water (Figure 7-13). Ultrafiltration of whole milk can be performed when the pressure across the membrane is approximately 1 bar and when the temperature is about 55 °C. However, the whole milk flux will be less than that obtained with skim milk. Ultrafiltering milk at 60 °C to 63 °C increases the flux and the growth of micro-organism is inhibited (Wasltra, 1981).

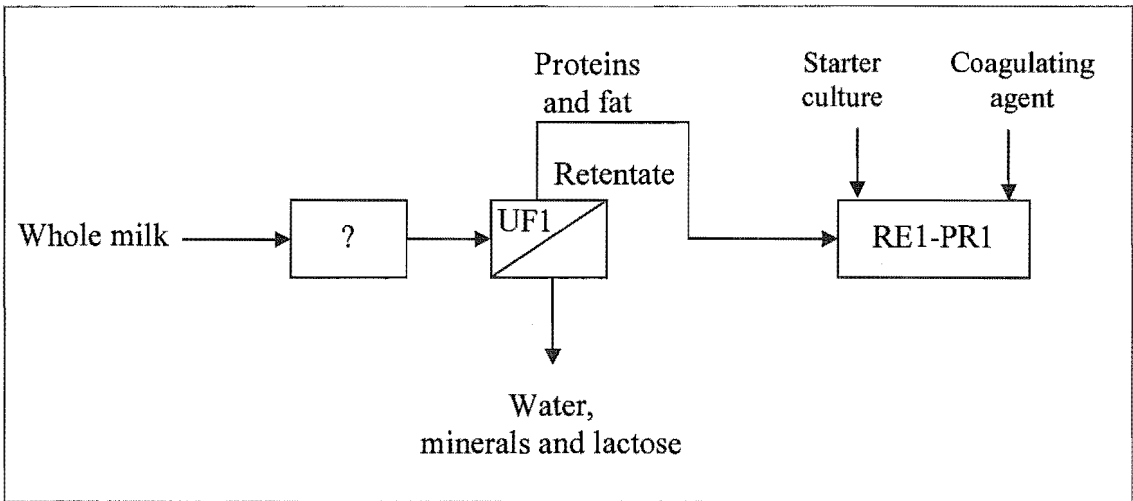


Figure 7-13 Ultrafiltration for protein concentration.

In Option 3, nanofiltration is used to concentrate the milk by dewatering and demineralising the milk. Therefore, less whey has to be removed downstream. The drawback here is that lactose will be retained. Lactose is not required in the cheese process except to produce lactic acid for the reaction. However, lactose can be separated downstream with whey (see Figure 7-14).

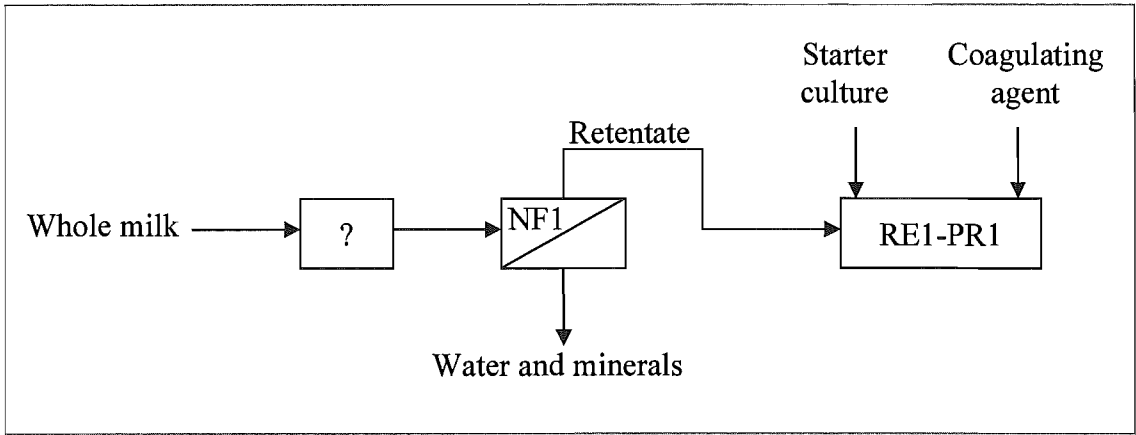


Figure 7-14 Nanofiltration for water total solid concentration.

Nanofiltration is rejected here because it retains most of the lactose which it is not required in the cheese process except for a small amount.

In Option 4, reverse osmosis is another alternative to concentrate milk by the removal of the water component (Figure 7-15). In practice, due to the concentration polarisation at the membrane, it will need a considerably higher pressure. Reverse osmosis is rejected here because cottage cheese requires only small amount of water removal.

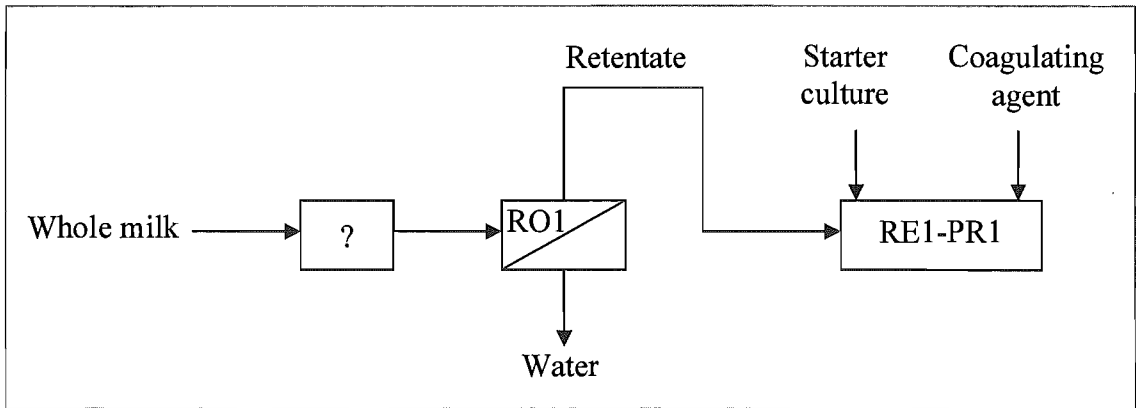


Figure 7-15 Reverse osmosis for water separation.

In Option 5, it is possible to use evaporation to concentrate the milk to be fed to the key process. Evaporation can concentrate the milk to approximately 50% total solids (see Section 4.2.3). Evaporation does not only increase the concentration of fat and protein content, but also the lactose and mineral content which is undesirable for the composition of cottage cheese (see Figure 7-16).

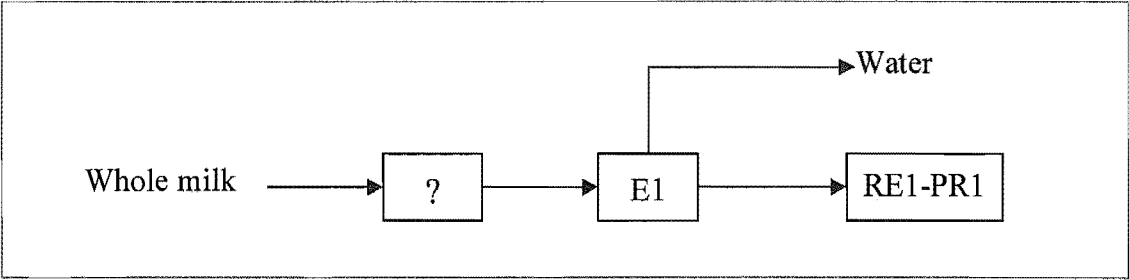


Figure 7-16 Upstream evaporation process.

For Option 6, fat separation is achieved by centrifugal separation (see Section 4.2.2). This option is a good candidate to produce the feed for the key process operation shown in Figure 7-17.

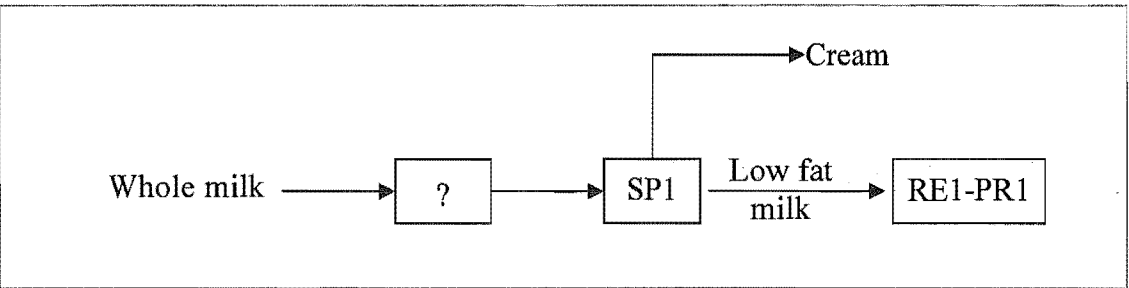


Figure 7-17 Centrifugal separation for low fat milk standardisation.

For Option 7, wet blending can be used to add any ingredient like fat if required. (Figure 7-18). Addition of salt at this stage would likely inhibit the subsequent reaction.

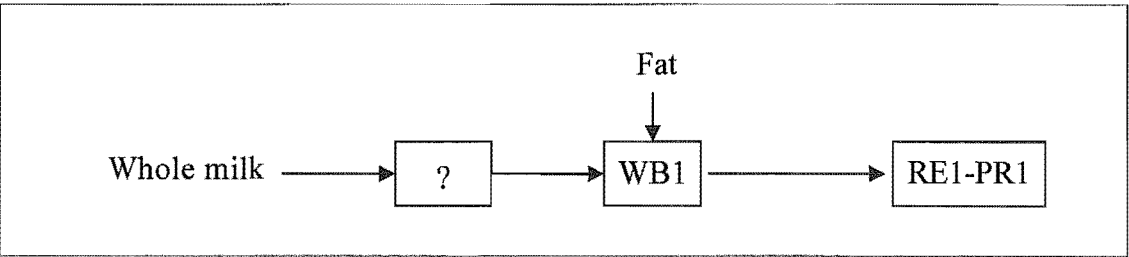


Figure 7-18 Wet blending for adding a fat component.

Out of these seven alternatives from Table 7-12, there are more possible combinations as shown in Table 7-13. Of these possible combinations, only those marked with an asterisk (*) are considered further as examples. Processes that cannot be developed further are marked with strikethrough and processes not to be considered here are not marked. Less conventional alternative process options are marked with a club (♣).

Table 7-13 Possible further combination options.

Fig.	Upstream Options	Fig.	Downstream Options
7-11	MF_a-(RE-PT)-	7-8	SP-WB-P
7-12	MF _b -(RE-PT)*	7-9	SF-WB-P*
7-13	UF-(RE-PT)♣		
7-14	NF-(RE-PT)-		
7-15	RO-(RE-PT)-		
7-16	E-(RE-PT)♣		
7-17	SP-(RE-PT)*		
7-18	WB-(RE-PT)♣		

Out of these eight options, separation is regarded as the best alternative to fulfil the product requirement of fat depletion calculated in Step 4. Then, pathogen control needs to be considered at the beginning of the process.

A final process flowsheet achieved is shown in Figure 7-19 below.

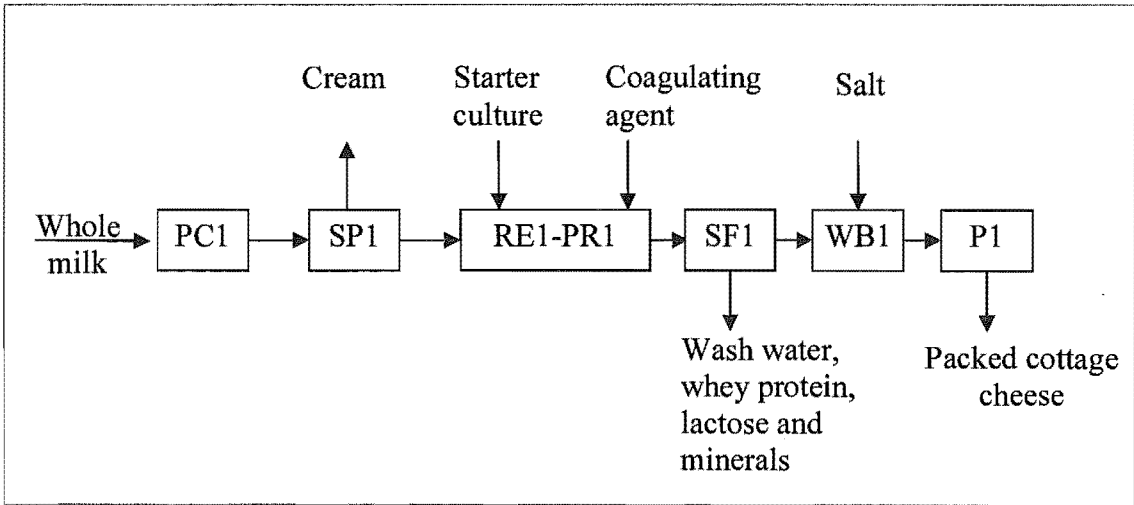


Figure 7-19 Schematic flowsheet of cottage cheese production.

The methodology will also produce many alternatives flowsheets e.g., (Figure 7-20).

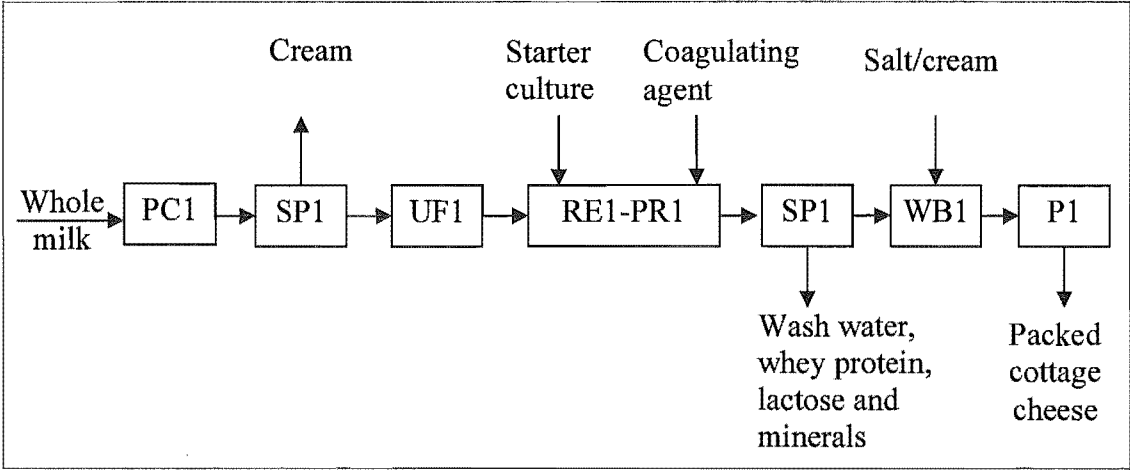


Figure 7-20 Schematic flowsheet option of cottage cheese production.

At the scale of this process, the cost of extra operations is probably not worthwhile.

Utilities and effluents from the separation process are shown in Table 7-14.

Table 7-14 Process utilities and emission.

Utilities required	Emissions
Steam	Smell
Electricity	Noise
Potable water	CIP water, cleaning agents
Hot water	
Cooling water	
Demineralised water	
CIP water, cleaning agents	

Step 10: *Check for each side products from the linear flowsheet. Classify them as co-products, by-products and waste products (see Section 3.3).*

Product: Packed cottage cheese

Co-product: Cream

Whey protein

Lactose

Minerals

Effluents: Water and detergent from CIP.

Step 11: *If it is a co-product, treat it as a new feed to the further processing and repeat the design methodology from Step 1.*

There is a significant volume of whey co-products produced from cottage cheese manufacture. This stream contains valuable components, namely, whey protein, lactose and minerals. However, at its low rate (3744 kg/day of whey; see Appendix A), it is unlikely to be economically viable for further processing.

The other co-product stream contains valuable component, namely cream. The cream will be treated as a new feed for further processing. The methodology will be repeated with the cream powder as the final product (i.e. Step 1). The details of Step 2 to 4 are not shown here. A freeze drier is chosen as the key process in Step 5. In Step 6, an economic analysis has been done in Appendix A for this key process. It shows that freeze drying of cream into cream powder is marginally unviable.

At this small volume 191.2 kg/day of fat (see Appendix A), it is also unlikely to be economically viable for further processing. Thus, this cream will be sold to a small dairy factory for homemade butter processing.

Step 12: *If it is a by-product or waste product, look for opportunities to off-set cost of discharging otherwise determine a suitable treatment for its disposal.*

Process integration options on small scale operations are typically limited. Integration of utilities in this case study is not considered.

Step 13: *Identify the matching streams within the flowsheet. Consider products and equipment constraints. Check for energy, water, time and environmental integration opportunities.*

There is no matching product within the flowsheet.

Step 14: *Identify the matching products between flowsheets (linear flowsheet and the new co-product processing flowsheets). Check for energy, water, time and environmental integration opportunities.*

There is no matching product between the flowsheet.

Step 15: *If the co-product cannot be processed due to the capacity problem, it may be necessary to identify the proximity matching product between sites and environment.*

The whey co-product will be disposed of as stock feed. If this cottage cheese production is carried out on a medium or large scale, then it may become practical to process the whey co-products stream to recover the valuable components.

None of the utilities and emissions can be matched for further integration.

7.4.2 Medium Scale Milk Processing

Overview

For the purpose of illustration, a medium scale process case study will be evaluated using the conceptual design methodology. The process shown here is proposed as a mean of identifying other factors that significantly affect the design opportunities, such as the process scale.

7.4.2.1 Case Study Three: Medium Scale Milk Processing (Packed Casein Powder)

Design Methodology

Step 1: *Select the final product.*

The choice of product is based on the market demand, and as an example, the product chosen here is packed casein powder.

Step 2: *List the composition of process feed and specifications of the final product.*

Feed = 10^6 kg raw whole milk per day

The composition of feed, product composition and specification are listed in Table 7-15.

Table 7-15 Composition of feed and product specification (Bylund, 1995).

Components	Composition of feed	Product specification
	[% w/w]	[% w/w]
	Wet basis	Wet basis
Fat	3.90	1.4
Casein protein	2.60	85.0
Whey protein	0.65	0.5
Lactose	4.60	0.1
Minerals and miscellaneous	0.95	1.5
Water	87.30	11.5
TS	12.70	88.5

Step 3: *Calculate the mass flow of feed and product*

Mass flow of feed = 1×10^6 kg raw whole milk per day.

$$\text{Mass flow of product} = \frac{\left(\text{flowrate of feed} \right) \times \left(\frac{\% \text{ casein}}{\text{in feed}} \right) \times \left(\frac{\% \text{ yield of casein in process}}{\% \text{ casein in product}} \right)}{\left(\frac{\% \text{ casein}}{\text{in product}} \right)} \quad (7-2)$$

$$= \frac{1000000 \text{ kg/d} \times 2.6 \% \times 99 \%}{85.0 \%}$$

Mass flow of product = 30282 kg of casein per day.

If 1 day = 20 production hours,

Mass flow of product = 1514 kg hr⁻¹

The component mass balance is determined by the percentage of casein yield (99%). The spreadsheet calculation of this component mass balance is in Appendix B.

Step 4: *Compare product composition with the feed to determine enrichment and/or depletion of components.*

Table 7-16 shows the milk components that need to be enriched and depleted. It shows that from the component calculations (see Appendix B), all milk components except for casein need to be depleted. Casein will be slightly depleted, but this is simply due to the yield of casein being less than 100% (due to the processing losses). If the casein losses exceed 1%, then the required depletion of all other components will need to be higher in order to maintain the desired product composition.

Table 7-16 The addition and removal of components.

Component	Enrichment [kg hr ⁻¹]	Depletion [kg hr ⁻¹]
Fat		1929
Casein		13
Whey protein		317
Lactose		2298
Minerals and miscellaneous		452
Water		43476

Step 5: *Select key process operation from Table 7-3 (based on Chapters 4 and 5).*

According to Table 7-3, (based on Section 5.6.1), the key process operation for the casein powder is precipitation. Therefore, a precipitation agent would be required.

Step 6: *Define the scope of the key process operation from the feed to its product and relate the operation feed and product to the overall process feed and product. Designate a letter from Table 7-2 to the process. Estimate the capital cost of the flowsheet and check its economic viability.*

The precipitation agent is the only component to be added. The precipitation agent used here is sulphuric acid of 10% strength (for casein process information see Section 5.6.1). Casein curd also need to be ‘cooked’ (see Section 5.6.1). Figure 7-21 shows the scope of the process for the production of casein.

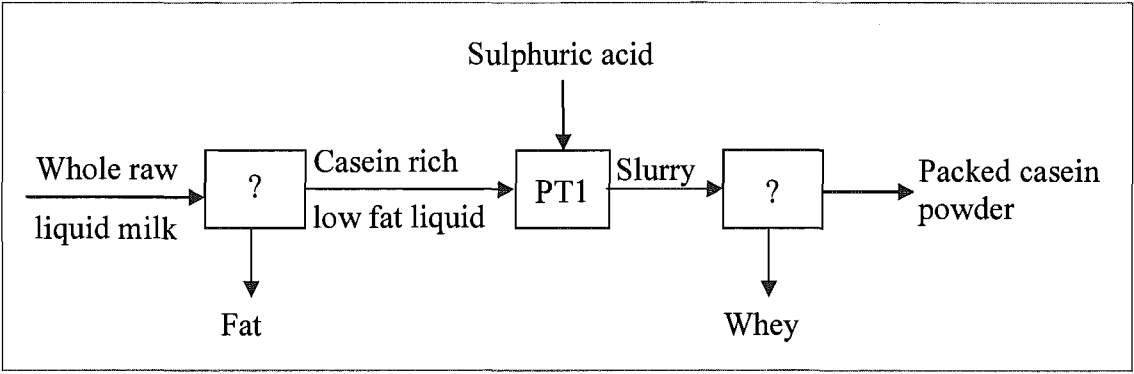


Figure 7-21 Casein production process scope.

Step 7: *Identify the requirements for the inputs, outputs and constraints of the selected key process operation (see Chapter 4).*

From the calculations in Appendix B, the casein protein is precipitated from low fat liquid containing casein (refer to Section 5.6.1). Therefore, the precipitation should be carried out with a minimum amount of fat. Consequently, an upstream fat separation is required.

Inputs: Feed has to be low fat liquid containing casein (see Section 5.6.1).

Precipitation agent

Outputs: Product is a slurry

Step 8: Downstream processes:

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the last operation in the flowsheet does not produce the overall process product:

Find all operations that can process feeds the same as the current flowsheet product. For each of these:

If the new operation is feasible:

- *Give it an identification.*
- *Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.*
- *Calculate the component and overall mass flows for the main product and side products.*
- *Itemise utilities/effluents/timing.*
- *Estimate the capital cost of the flowsheet and check its economic viability.*
- *Call this step recursively.*

Precipitation does not produce the final product since whey protein needs to be removed in order to recover the casein precipitate (Figure 7-22).

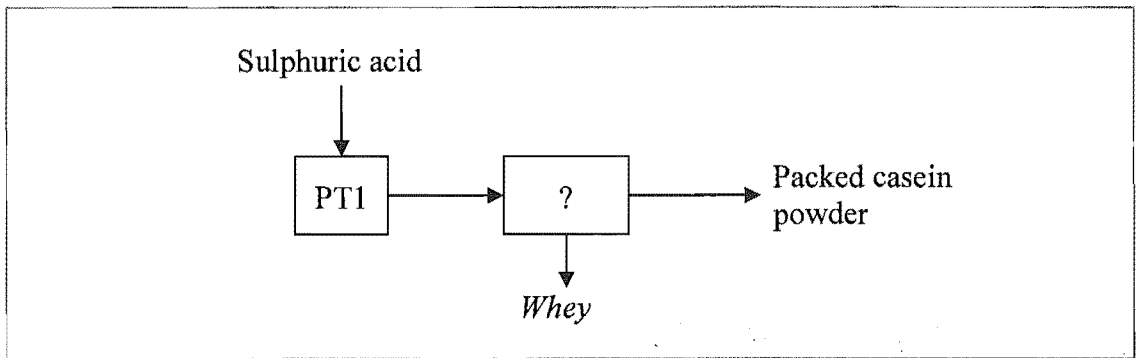


Figure 7-22 Downstream processes

From Table 7-2, it is found that there are five processes that can process the product from the key process product stream. These are shown in Table 7-17.

Table 7-17 Downstream process options for operation after the key process operation.

Process option	1 st Consideration
Option 1	PT1-SP1
Option 2	PT1-SF1
Option 3	PT1-WB1
Option 4	PT1-ST1
Option 5	PT1-P1

In Option 1, a centrifugal separator (decanter) is designed to separate casein from whey (Figure 7-23). There are also other different types of decanter in the dairy industry such as the conveyor-bowl centrifuge (see Section 4.2.2).

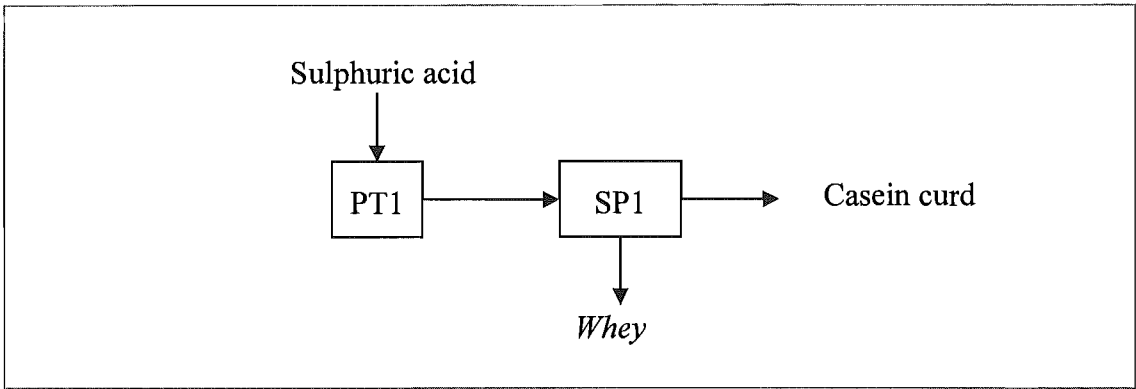


Figure 7-23 Centrifugal separation for casein process.

Option 2 uses a filtration screen to separate whey from the casein curds (Figure 7-24). There are a variety of screen filter types, including those using rotary, inclined or parabolic fine mesh screens for continual removal of the casein curds. Cross-flow filtration is commonly used for the separation of whey or wash water from casein or cheese curd (see Section 4.2.1.2).

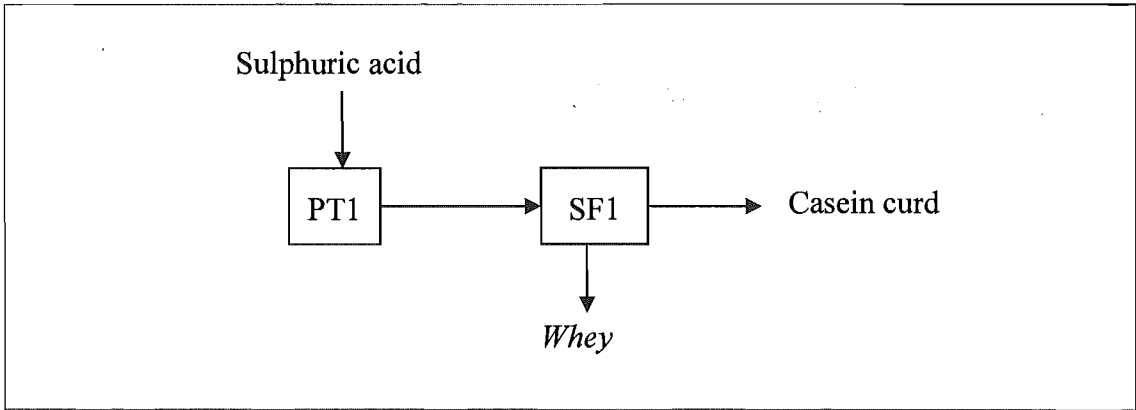


Figure 7-24 Screen filtration for casein.

In Option 3, a wet blending option is rejected in the first consideration because nothing needs to be added to the slurry. Only component removal is required.

Option 4 that considers a storage of the key process product is rejected because there is no good reason for storing the slurry. Furthermore microbial growth might occur.

Option 5 which considers the packing is also rejected because the product, from the precipitation process, has not achieved the final product specification at this stage.

From this analysis, there are two options left out of the five options in Table 7-17 that can process the key process product; centrifugal separation and screen filtration. Process options derived from these first considerations are numerous as shown in Table 7-18. Only those marked with an asterisk (*) are realistic considerations to take further as examples. Processes that cannot be developed further are marked with strikethrough. Possibly feasible processes but not considered here are not marked. Less conventional alternative process options are marked with a club (♣).

Table 7-18 Possible downstream processes of the key process operation.

Process option	1 st Consideration	2 nd Consideration	3 rd Consideration	4 th Consideration
Option 1	PT1-SP1	PT1-SP1-SF1	PT1-SP1-SF1-WB1 PT1-SP1-SF1-P1	PT1-SP1-SF1-FB1-P1 PT1-SP1-(WB1-SF1)-SP2-FB1-P1
		PT1-SP1-WB1	PT1-SP1-WB1-SF1*	
		PT1-SP1-P1		
Option 2	PT1-SF1*	PT1-SF1-SP1	PT1-SF1-SP1-WB1♣ PT1-SF1-SP1-P1	PT1-SF1-SP1-WB1-SF2
		PT1-SF1-WB1	PT1-SF1-WB1-SF2*	PT1-SF1-WB1-SF2-FB1-P1*
		PT1-SF1-P1		
Option 3	PT1-WB1			
Option 4	PT1-SF1			
Option 5	PT1-P1			

Both Option 1 and 2 seem to be good alternatives, that will achieve the desired separation. However screen filtration (SF) is preferred since it has lower capital and operating cost than centrifugal separation.

In the second consideration in Table 7-18, the option chosen above does not produce the final product because the casein curd still contains excess lactose, minerals and whey proteins (see Appendix B). It needs to be refined by washing out the whey protein, lactose and minerals.

Warm water is added into a wet blending process for washing out the whey from the casein curd. This is followed by screen filtration, in order to purify the casein product (see Section 5.6.1). This is shown in Figure 7-25. The WB-SF2 step (washing) can be repeated if necessary to obtain higher purity.

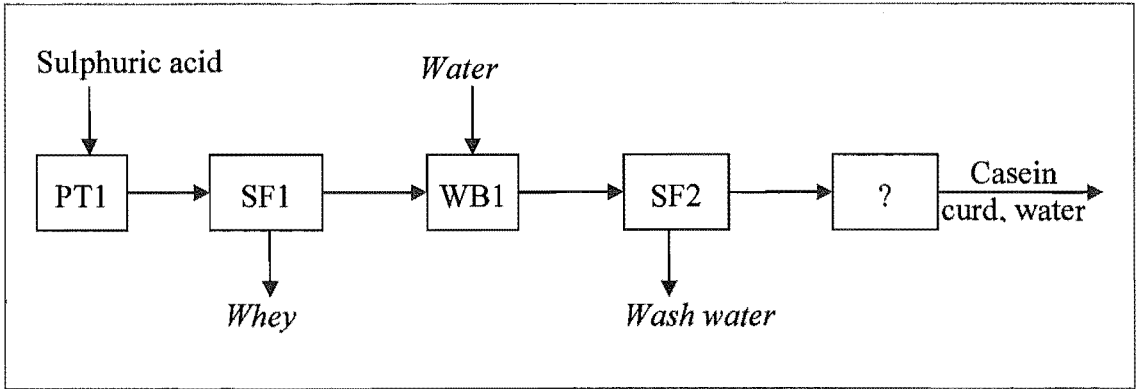


Figure 7-25 Screen filtration for casein production.

The product at this stage is a solid curd containing moisture. The moisture needs to be removed to meet the product specifications. From Table 7-2, there are three operations that can process this product. They are, centrifugal separation, dry blending and fluidised bed drying.

Centrifugal separation using a decanter or screen centrifuge can be used to remove more moisture, however it is unlikely to remove sufficient water to directly achieve the desired product specification.

Dry blending can be used but it is not considered in this case. However, casein can be blended with itself to produce a more uniform product.

Fluidised bed drying can follow screen filtration to remove the remainder of the water from the casein curd in order to meet the product specification as shown in appendix B (see Figure 7-26). This is selected as the preferred option for producing dried casein.

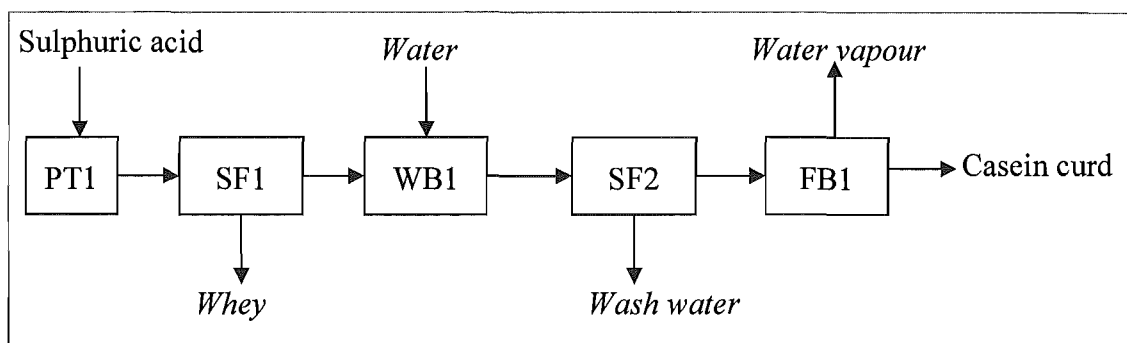


Figure 7-26 Fluidised bed drier for casein production.

Now, the product has achieved its product specification and only requires to be packed (see Figure 7-27).

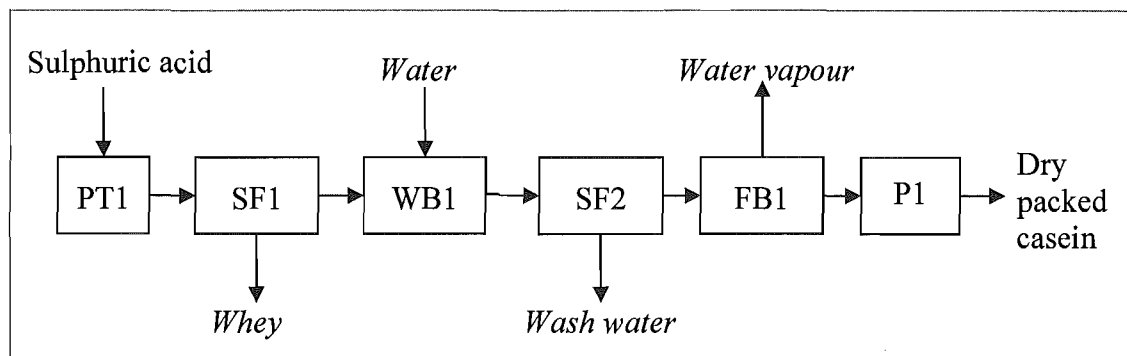


Figure 7-27 Screen filtration for casein production.

See Section 5.6.1 for the utilities associated with the casein process.

Step 9: Upstream processes:

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the first operation in the flowsheet is not fed by the overall process feed:

Find all operations that can produce the feed for the current flowsheet.

For each of these:

If the new operation is feasible:

- *Give it an identification.*
- *Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.*
- *Calculate the component and overall mass flows for the main product and side products.*

- *Itemise utilities/effluents/timing.*
- *Estimate the capital cost of the flowsheet and check its economic viability.*
- *Call this step recursively.*

The calculation in Appendix B shows that the fat from the whole milk needs to be separated (see Figure 7-28) before the key process.

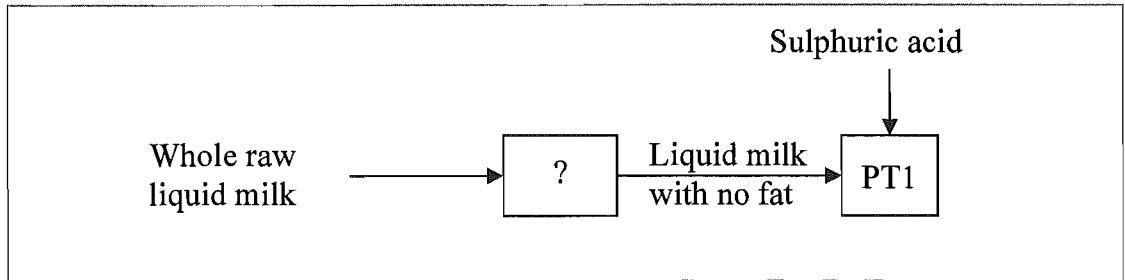


Figure 7-28 Schematic flowsheet upstream of the key process.

From Table 7-2, there are 11 options to deplete components upstream of the key process (see Table 7-19).

Table 7-19 Process options that can produce the feed for the current flowsheet.

Process option	1 st Consideration
Option 1	MF1 _a -PT1
Option 2	MF1 _b -PT1
Option 3	UF1-PT1
Option 4	NF1-PT1
Option 5	RO1-PT1
Option 6	ED1-PT1
Option 7	DI-PT1
Option 8	IX1-PT1
Option 9	E1-PT1
Option 10	SP1-PT1
Option 11	WB-PT1

From Table 7-19, the unit operations that can produce liquid feed for the current flowsheet feed are examined in each option and further alternatives explored.

Option 1, loose microfiltration membrane (MF_a1) can be used to remove the fat and micro-organisms from whole milk (Figure 7-29). However there will be significant casein losses in the retentate which will reduce the overall casein yield (Bylund, 1995).

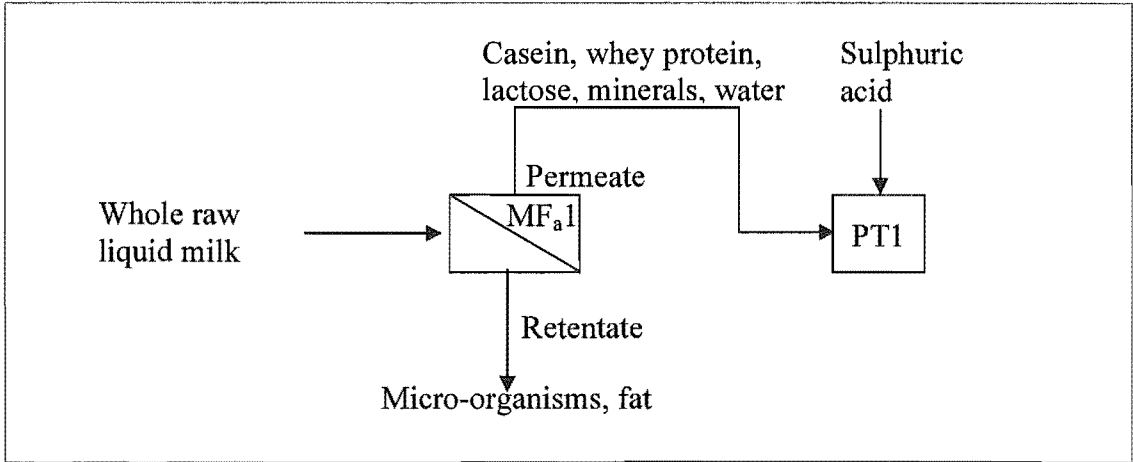


Figure 7-29 Schematic flowsheet with loose MF_a upstream of the key process.

Option 2, tight microfiltration (MF_b1) can be used to achieve partial depletion of whey protein, lactose, minerals and water (see Figure 7-30). There is no casein losses for this option therefore it is a good candidate. Given that the feed to precipitation must be low in fat, excess fat must be removed prior to this process. Similarly a pathogen control step must also exist prior to this process. Upstream removal of water, whey protein, lactose and minerals reduces the volume of material that must pass through the key process, and will also lessen the amount of washing required downstream.

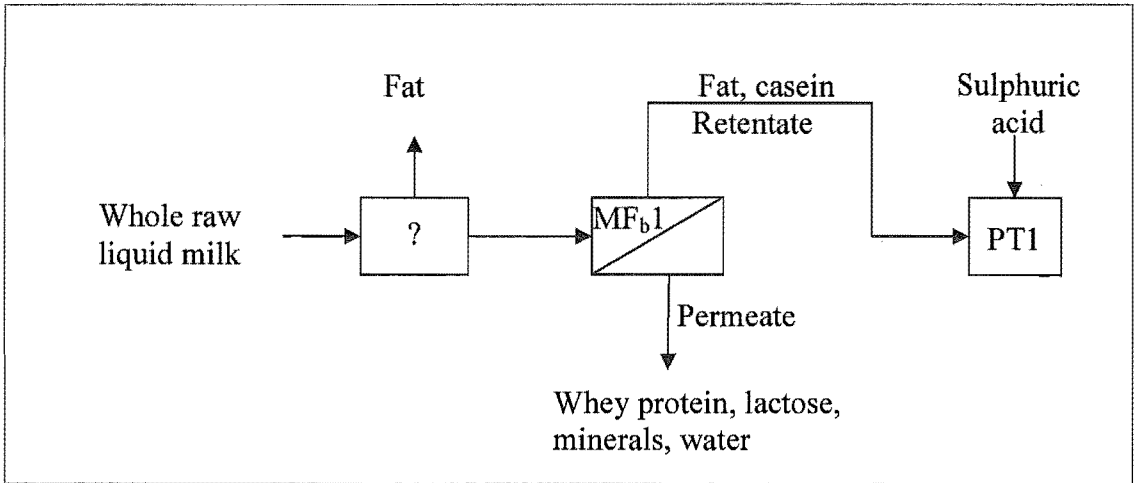


Figure 7-30 Schematic flowsheet with MF_b upstream of the key process.

For Option 3, ultrafiltration can be used to produce concentrate skim milk that is rich in proteins and depleted in lactose, minerals and water (Figure 7-31). This potentially provides an uncontaminated source of lactose. In this option there are no casein losses, and downstream washing might be reduced, however UF is not as appealing as MF, since ultrafiltration retains whey proteins. Excess fat removal upstream is still required.

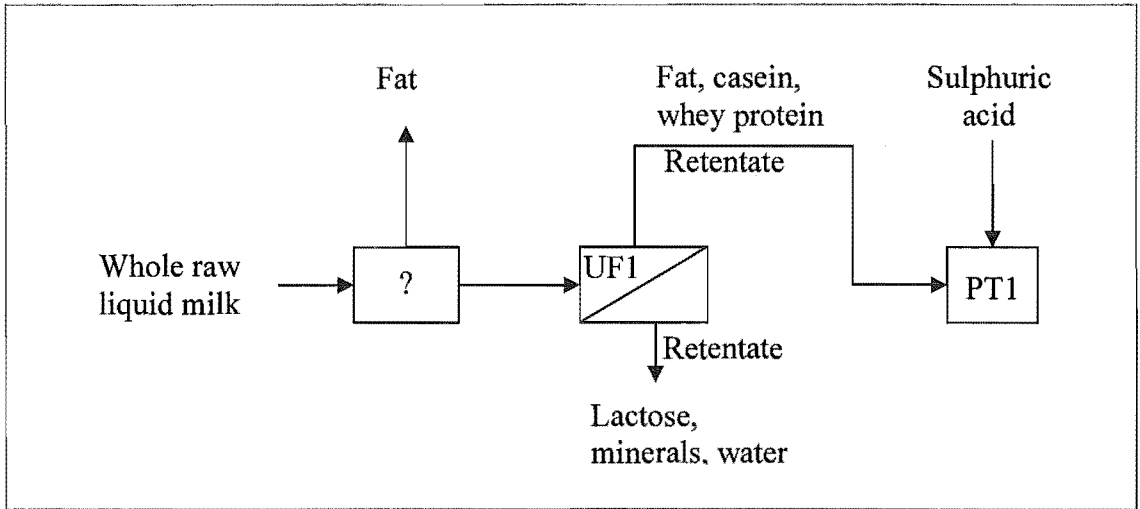


Figure 7-31 Schematic flowsheet with UF upstream of the key process.

For Option 4, nanofiltration can be used to concentrate the skim milk by removal of minerals and water (Figure 7-32). In this option there are no casein losses, and downstream washing is reduced, however NF is not as appealing as UF since lactose is retained by the membrane. Excess fat removal upstream is still required.

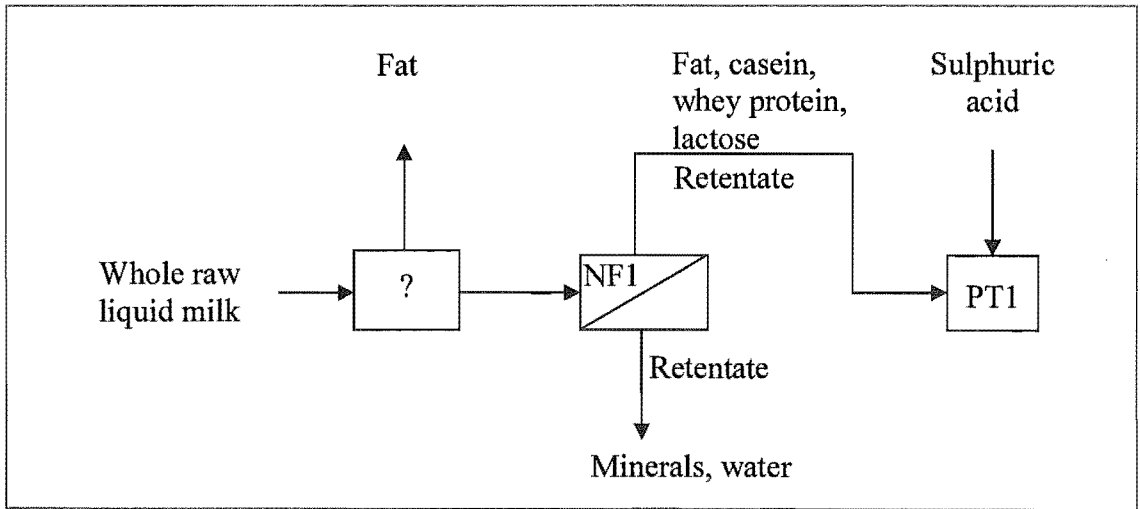


Figure 7-32 Schematic flowsheet with loose NF upstream of the key process.

For Option 5, reverse osmosis prior to precipitation is a viable membrane concentration of skim milk by removing water (Figure 7-33). This process offers no advantage over UF. While it might provide a source of clean water, it will not reduce the wash water requirement downstream. Excess fat removal upstream is still required. This option is discarded.

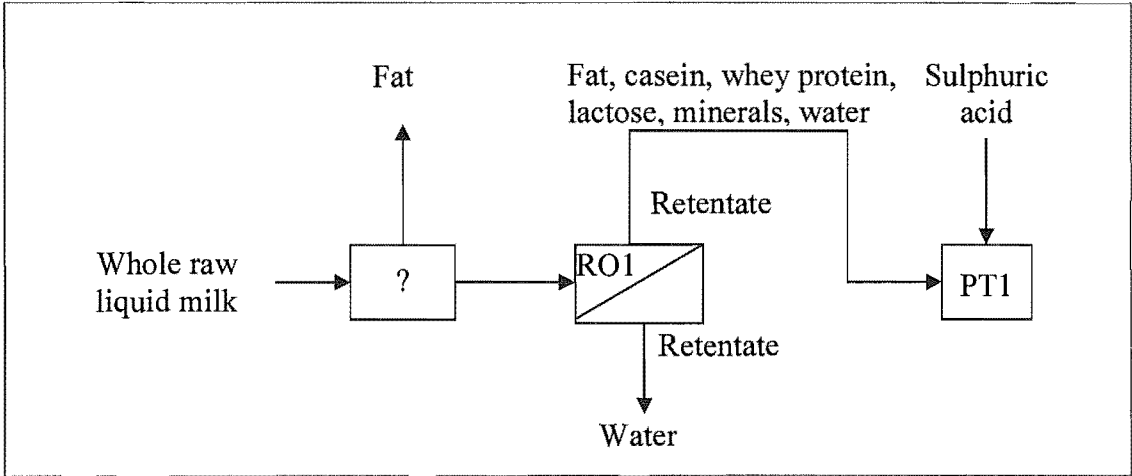


Figure 7-33 Schematic flowsheet with RO upstream of the key process.

For Option 6, electrodialysis (Section 4.2.1.2) can be used for milk demineralisation. (Figure 7-34). However, like NF this only offers limited advantages, and excess fat must still be removed upstream. There is no obvious advantage of mineral reduction without lactose reduction so this process is rejected.

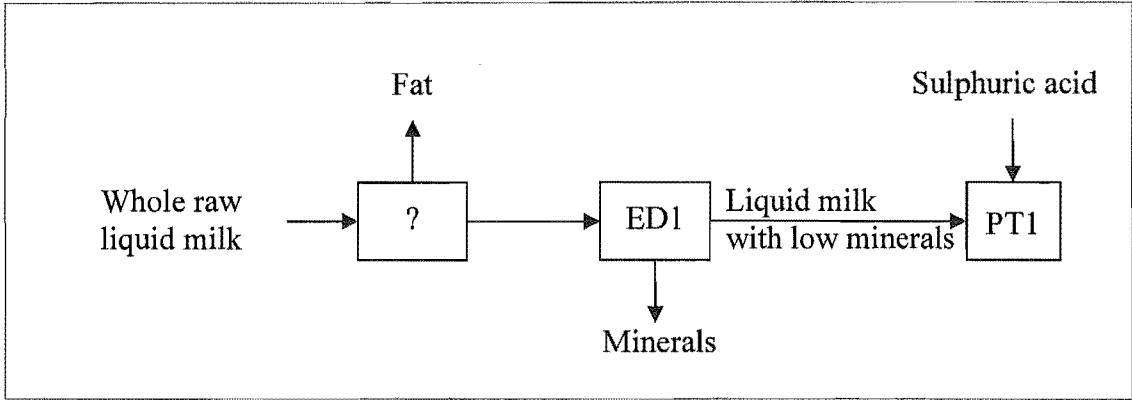


Figure 7-34 Schematic flowsheet with ED upstream of the key process.

Option 7, dialysis (Figure 7-35) also removes minerals from the skim milk stream. This process is discarded for the same reasons as NF and electrodialysis.

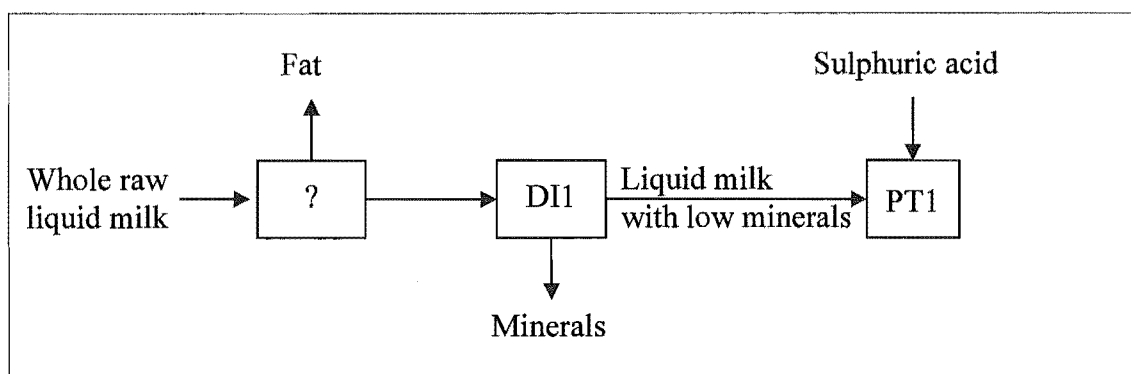


Figure 7-35 Schematic flowsheet with DI upstream of the key process.

For Option 8, ion exchange can also achieve demineralisation of milk (Figure 7-36). This process is discarded for the same reasons as NF, electrodialysis and dialysis.

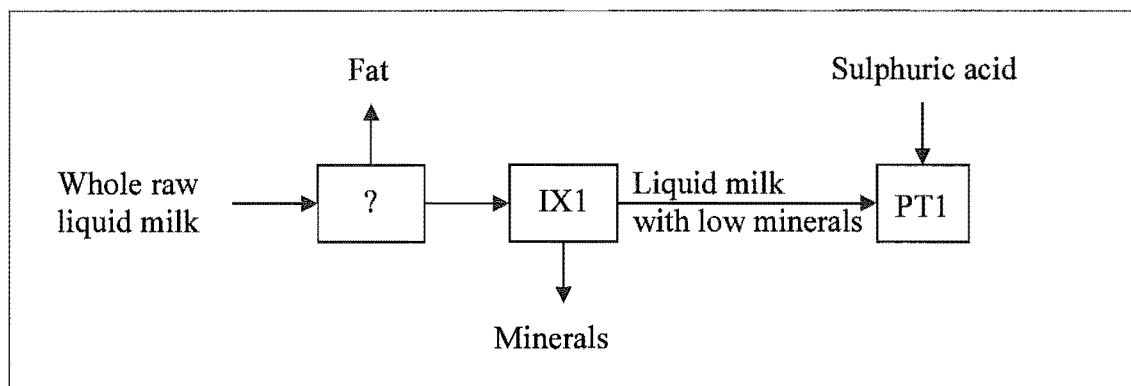


Figure 7-36 Schematic flowsheet with IX upstream of the key process.

For Option 9, evaporation can be used to concentrate milk by the removal of water (Figure 7-37). Like RO, evaporation is rejected since it offers no significant advantages to justify the capital and operating cost of the unit operation.

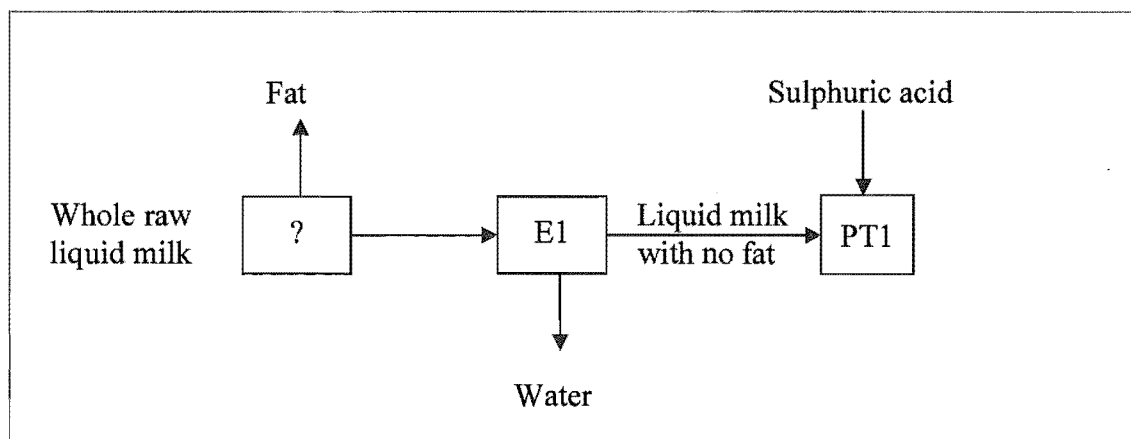


Figure 7-37 Schematic flowsheet with E upstream of the key process.

For Option 10, centrifugal separation can be used to separate fat from whole milk (Figure 7-38). The operation generates two streams; skim milk (fat depleted) and cream (fat enriched). Mass balances (Appendix B) showed that the desired product specification can only be achieved if excess fat is removed upstream of the key process. This option is superior to loose microfiltration, since casein losses are much lower. Centrifugal separation is selected as the preferred method to generate a low fat feed stream to the key process.

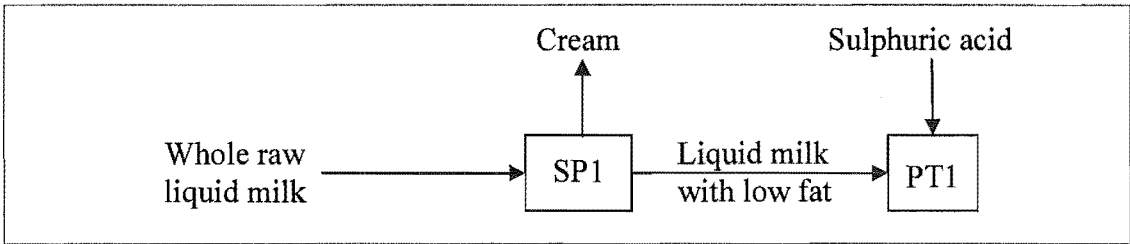


Figure 7-38 Schematic flowsheet with SP upstream of the key process.

For Option 11, wet blending cannot be used because there is nothing to add.

From Table 7-19, there are two options to produce a low fat feed to the key process: loose microfiltration and centrifugal separation. Centrifugal separation is selected for this case study. Both tight microfiltration and ultrafiltration deplete unwanted components, reducing the amount of curd washing required downstream of the key process. Tight microfiltration is the preferred option, since it achieves partial depletion of whey protein, which ultrafiltration cannot. Mass balance calculations in Appendix B show that the use of tight microfiltration reduces wash water requirements by 40%. Energy requirements for curd cooking and cooling are also reduced, due to liquid volumes passing through the key process. The upstream flowsheet with both centrifugal separation and tight microfiltration is shown in Figure 7-39.

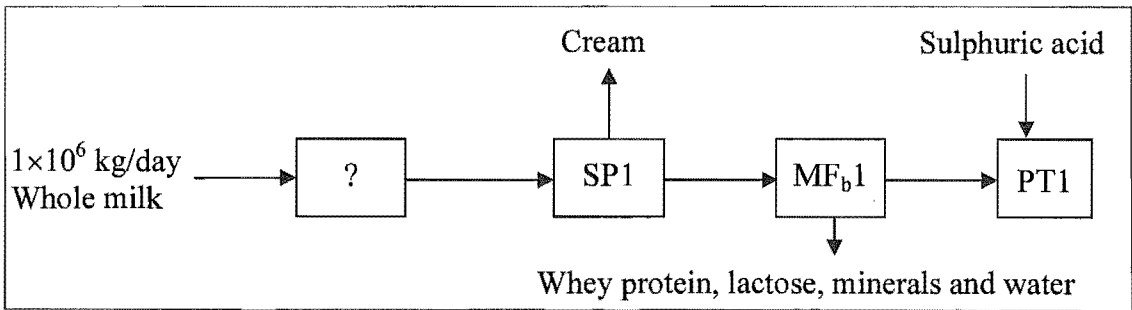


Figure 7-39 Schematic flowsheet of fat separation upstream key process.

Food safety and longer shelf life demand that milk should be pathogen controlled (see Sections 4.1 and 4.8), as shown in Figure 7-40.

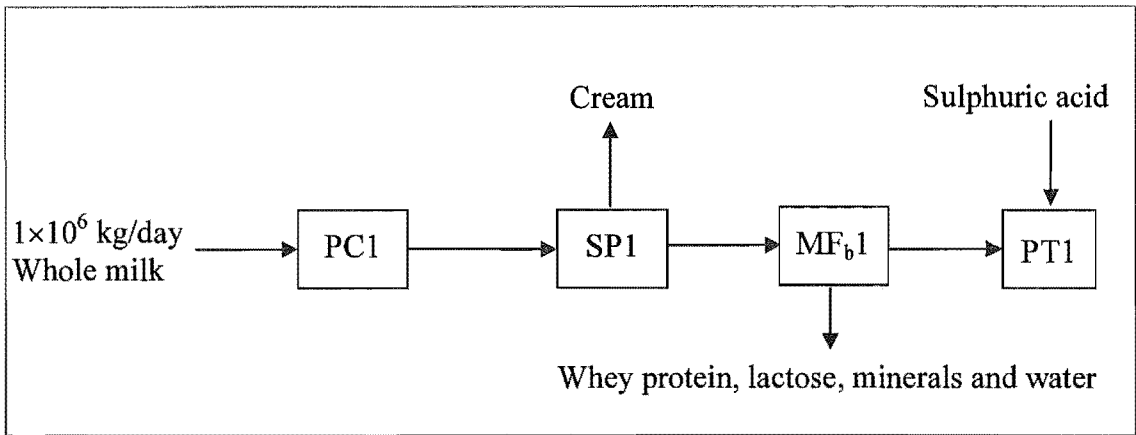


Figure 7-40 Schematic flowsheet of pathogen control upstream process.

One of many final linear process flowsheet is shown in Figure 7-41 below.

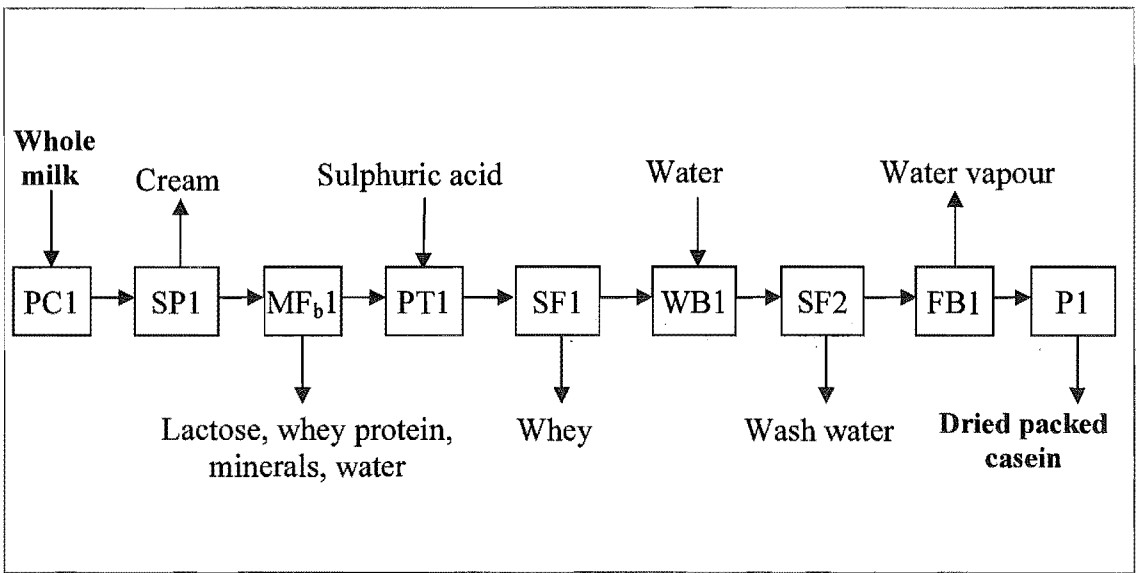


Figure 7-41 Final linear process flowsheet of packed dried casein.

Step 10: Check for each side products from the linear flowsheet. Classify them as co-products, by-products and waste products (see Section 3.3).

From Step 8 and 9 it can be seen most of the side products produced during casein manufacture are associated with purifying after precipitation (Figure 7-42). A variety of flowsheets are possible to achieve this.

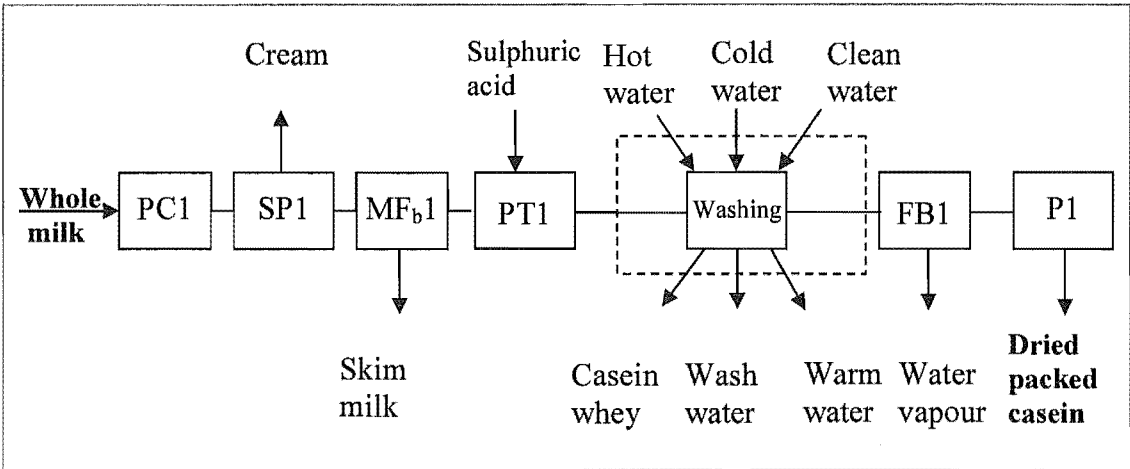


Figure 7-42 Side products from the linear flowsheet.

Figure 7-43 is one possible option for purifying casein curd, using multiple washing stages with wash water recycled. Casein whey co-product is still produced by this flowsheet. RO permeate is used in the last wet blending stage to produce the final curd wash water. Casein fines are removed from the combined whey and wash water streams by centrifugal separation, and recovered to the casein cooking line. These curd fines will be coagulated in the cook line.

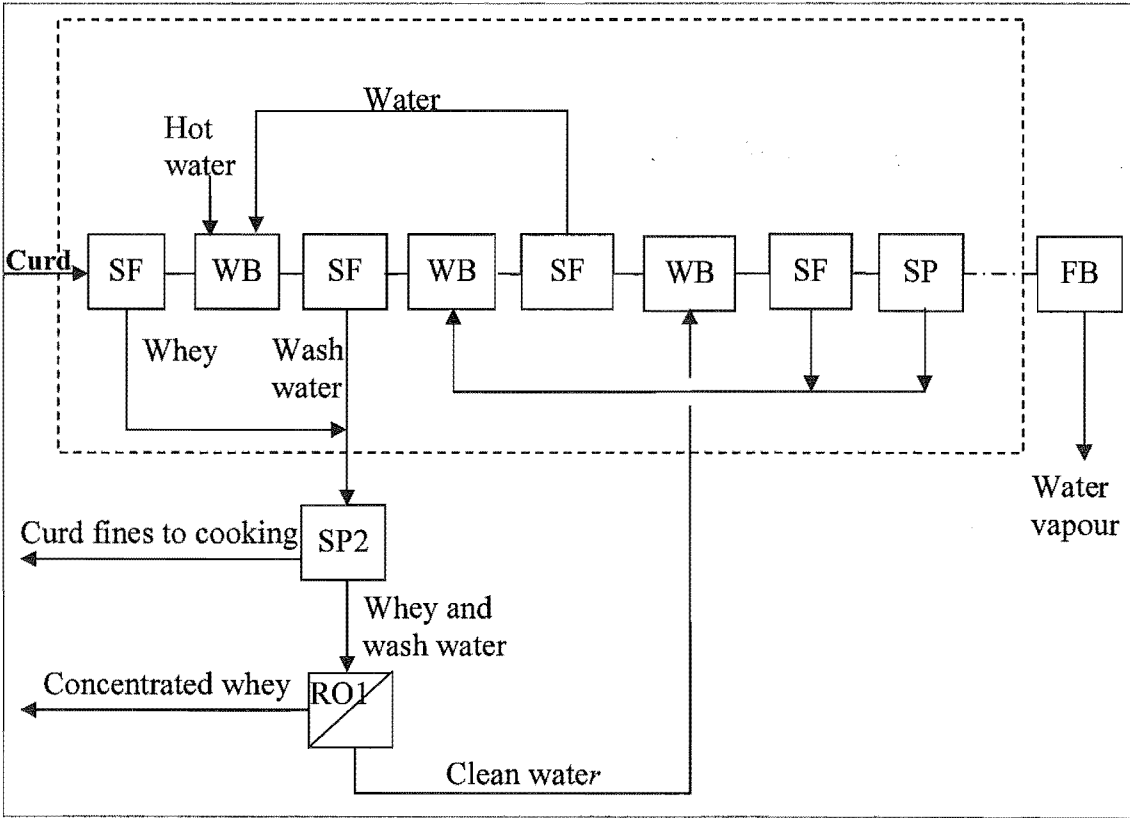


Figure 7-43 Possible process flowsheet with high degree of integration between curd washing side streams.

When formally examining possibilities for side stream integration, it is useful to present the relevant information in a structured format. Table 7-20 shows the inputs streams required for the casein flowsheet developed in Step 9. Values in the table are generated from mass and energy balances in Appendix B.

Table 7-20 Inputs required for the linear casein flowsheet (Figure 7-41).

Stream	Use	Flow [kg/hr]	Classification
Whole milk	Primary process feed	50000	Ingredient
Sulphuric acid	Injected into low fat milk to precipitate casein curd	20	Ingredient
Hot water	Used to heat curd to cooking temperature	9738	Utility
Clean water	Potable water added into dewheyed casein to wash out unwanted fat, whey protein, lactose and minerals.	10628	Ingredient

Table 7-21 shows the output streams from the casein flowsheet developed in Step 9. Values in the table are generated from mass and energy balances in Appendix B.

Table 7-21 Output streams from the linear casein flowsheet (Figure 7-41).

Stream	Description	Source	Flow [kg/hr]	Classification
Casein	Packed casein powder	Packing line	1434	Primary product
Cream	High solids stream. Primarily fat, with small amounts of casein, whey protein, lactose and minerals.	Centrifugal separator processing whole milk feed	4796	Co-product
Skim milk permeate	Low solids stream. Primarily lactose, with small amounts of whey protein and minerals.	Microfiltration plant processing skim from centrifugal separator	32348	Co-product
Casein whey	Low solids stream. Primarily lactose, with small amounts of fat, whey protein, minerals and acid. Also contains small amount of casein fines.	Filtration screen processing casein slurry	6234	Co-product
Wash water	Very low solids stream. Small amounts of whey protein, lactose and minerals. Also contains small amount of casein fines.	Cooked curd washing	10986	Co-product
Warm water	Clean, warm utility water	Heating curd to cook temperature	9738	Utility
Water vapour	Water vapour	Hot exhaust gas from fluidised bed drier	4864	By-product

Step 11: *If it is a co-product, treat it as a new feed to the further processing and repeat the design methodology from Step 1.*

There are four possible co-product streams produced by the proposed casein flowsheet shown in Figure 7-41, and summarised in Tables 7-20 & 7-21. Cream is a co-product that has immediate value without any further processing; it may be sent to another factory on site, or on-sold to another processor. In this case study it is assumed that cream is sent to another factory for processing. Skim milk permeate is also considered to have immediate value, since it can be injected directly into liquid milk, when producing milk powder with enriched lactose and minerals content. For this case study, it is assumed that the milk permeate is sent to used in another a factory without need for further processing.

The casein whey and wash water require further processing to produce a valuable product. It is likely to be necessary to remove the casein fines from the casein whey and wash water streams. Both streams are produced at the same time, and have very low solids, making it possible to combine the two streams. Thus for casein production, there are three potential co-product streams.

Step 12: *If it is a by-product or waste product, look for opportunities to off-set cost of discharging otherwise determine a suitable treatment for its disposal.*

The only by-product identified in Table 7-21 is water vapour from the fluidised drier. Discharging this does not have any associated costs.

Step 13: *Identify the matching streams within the flowsheet. Consider products and equipment constraints. Check for energy, water, time and environmental integration opportunities.*

One possible match is identified from Tables 7-20 and 7-21:

- 1) *Recover water from combined whey and wash water stream to use for curd washing.*
To achieve this, it is first necessary to remove the casein fines from this co-product stream. Centrifugal clarification (see Section 4.2.2) is selected to remove these fines. Clarifier fines can be recovered to cooking to increase the production yield. NF

treatment produces a permeate with some lactose and minerals content. Subsequent RO polishing of this permeate produces a stream that is (essentially) free of dissolved solids. Use of RO polisher permeate in the wet blending (curd washing) step reduces the clean water requirements by 96% (see Appendix B). Time integration is relatively simple, since the clean water and wash water streams are closely related, although additional supplementary water may be required at start-up until a permeate stream is available from the RO polisher. The NF and RO polisher retentate streams can be combined as a new co-product stream. The casein flowsheet with integrated side streams is shown in Figure 7-44.

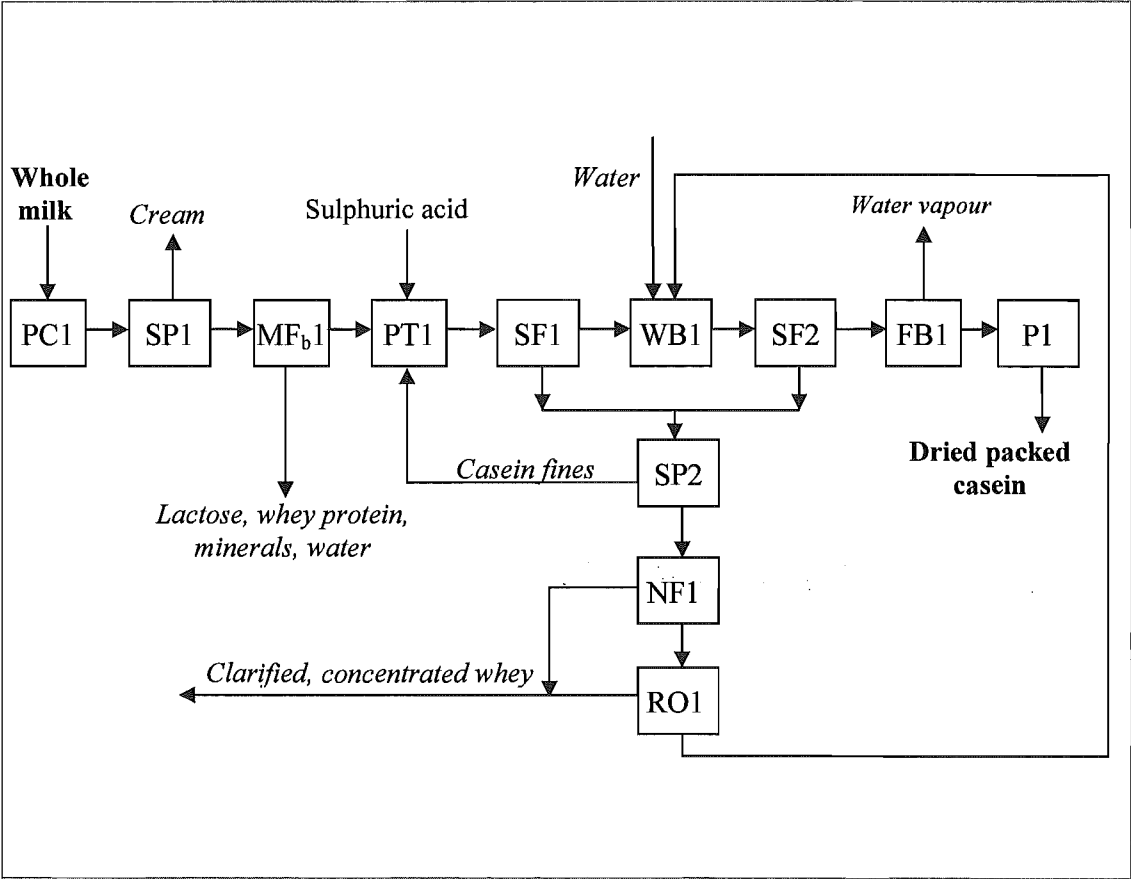


Figure 7-44 Process flowsheet of packed dried casein with integrated side streams.

Table 7-22 shows the input streams to the casein flowsheet developed in Step 13 after side streams have been integrated. Values in the table are generated from mass and energy balances in Appendix B. Values of note are marked in bold.

Table 7-22 Inputs required for casein flowsheet after integration of matching side streams.

Stream	Use	Flow [kg/hr]	Classification
Whole milk	Primary process feed	50000	Ingredient
Sulphuric acid	Injected into low fat milk to precipitate casein curd	20	Ingredient
Hot water	Used to heat curd to cooking temperature	9762	Utility
Clean water	Potable water added into dewheyed casein to wash out unwanted fat, whey protein, lactose and minerals.	454	Ingredient

Table 7-23 shows the output streams from the casein flowsheet developed in Step 13 after side streams have been integrated. Values in the table are generated from mass and energy balances in Appendix B. Values of note are marked in bold.

Table 7-23 Output streams from casein flowsheet after integration of matching side streams.

Stream	Description	Source	Flow [kg/hr]	Classification
Casein	Packed casein powder	Packing line	1434	Primary product
Cream	High solids stream. Primarily fat, with small amounts of casein, whey protein, lactose and minerals.	Centrifugal separator processing whole milk feed	4796	Co-product
Skim milk permeate	Low solids stream. Contains lactose, whey protein and minerals.	Microfiltration plant processing skim from centrifugal separator	32348	Co-product
Clarified, concentrated whey stream	Medium solids stream. Primarily lactose, with small amounts of fat, whey protein, minerals and acid. Free from casein fines.	Combined retentate streams from NF and RO polisher plants	6987	Co-product
Warm water	Clean, warm utility water	Heating curd to cook temperature	9762	Utility
Water vapour	Water vapour	Hot exhaust gas from fluidised bed drier	4910	By-product

Step 14: *Identify the matching products between flowsheets (linear flowsheet and the new co-product processing flowsheets). Check for energy, water, time and environmental integration opportunities.*

It was decided to produce WPC powder from the new combined co-product stream (NF RO polisher retentate). The process flowsheet developed for this case study consists of a ultrafiltration plant (the diafiltration), evaporator and drier producing a powder product. A low solids permeate stream that contains primarily lactose and minerals is also produced (see Appendix B for details). This flowsheet was developed by following Steps 1-12 of the design methodology described in this chapter initially.

In Step 13 a match was identified, for the recovery of water from the permeate stream for diafiltration to the ultrafiltration plant. Consequently, NF and RO polisher plants were added to the flowsheet to facilitate side stream integration. NF treatment followed by RO polishing would produce sufficient water to supply all WPC UF diafiltration requirements, with sufficient left to replace remaining potable water required for curd washing. Retentate streams from the NF and RO polisher plants should be combined as a single co-product stream. The NF plant and RO polisher are relatively well time integrated with WPC UF, although additional supplementary water may be required at start-up until a permeate stream is available from the RO polisher. However the RO and casein washing processes are less likely to be consistently time integrated, so it is recommended that the remaining permeate be sent to a silo, and used as required. Storage of this water would allow it be used for other purposes as required, such as CIPs of the casein and WPC plants. A second match was identified in Step 13 for the WPC flowsheet, involving recovery of heat from the evaporator to the NF and RO polisher plants. However an energy balance showed that the condensate could only supply 6% of the energy required to preheat the feed to the NF plant (Appendix B). Therefore, this match was discarded as being impractical. The final process flowsheet is shown in Figure 7-45.

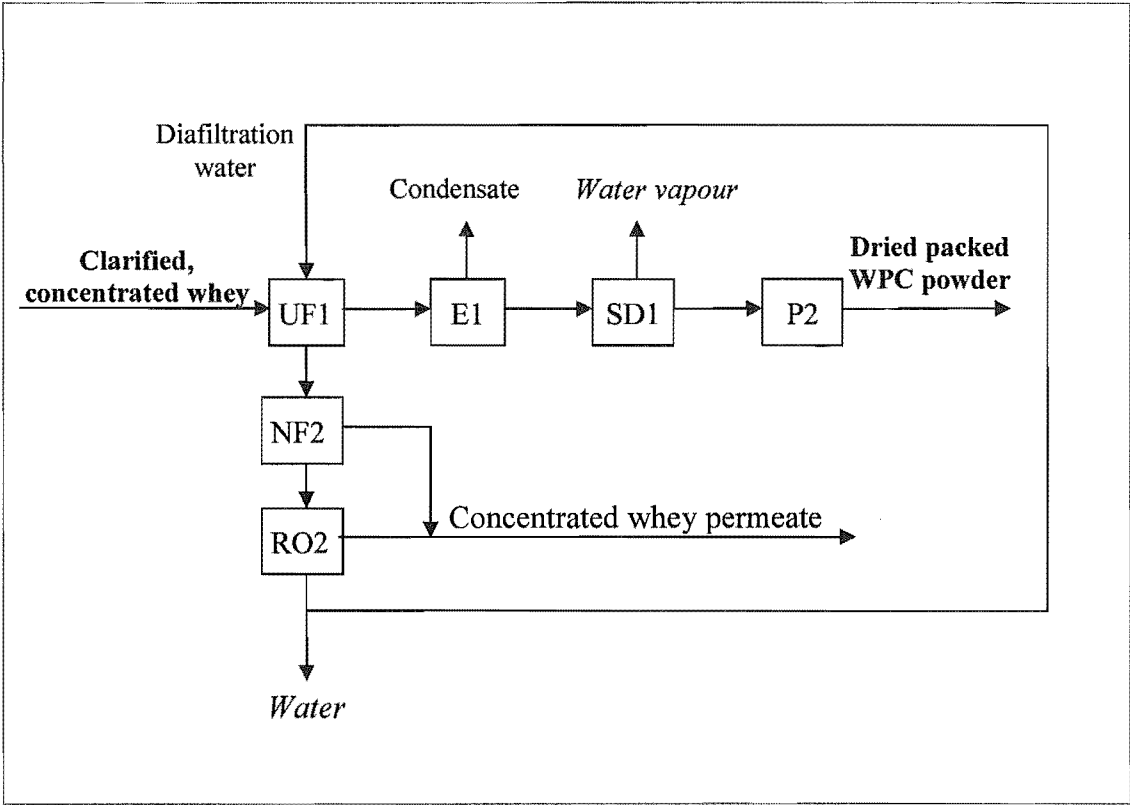


Figure 7-45 Process flowsheet of packed dried WPC with integrated side streams.

Table 7-24 shows the input streams required for the integrated WPC flowsheet. Calculations for this case study are presented in Appendix B.

Table 7-24 Input streams required for the WPC flowsheet with side stream integration.

Stream	Use	Flow [kg/hr]	Classification
Clarified, concentrated whey and wash water	Feedstock to UF plant for WPC production	6986	Ingredient

Table 7-25 shows the output streams from the WPC flowsheet. Calculations for this case study are presented in Appendix B.

Table 7-25 Output streams from the WPC flowsheet with side stream integration.

Stream	Description	Source	Flow [kg/hr]	Classification
Whey protein concentrate	Packed WPC powder	Packing line	166	Co-product
Concentrated whey permeate	Medium solids stream containing mainly lactose and minerals	Combined retentate streams from NF and RO polisher plants processing WPC UF permeate	3309	Co-product
Demineralised water	Clean water with very low minerals content	Permeate from RO polisher processing NF retentate	3850	Co-product
Evaporator condensate	Water condensate with no solids	Evaporator processing ultrafiltration plant retentate	266	Utility
Water vapour	Water vapour	Hot exhaust gas from spray drier	233	By-product

Step 15: *If the co-product cannot be processed due to the capacity problem, it may be necessary to identify the proximity matching product between sites.*

NF and RO extraction of water from the ultrafiltration permeate stream means that the co-product derived from WPC production is now a medium solids stream that is high in lactose and minerals. Such a stream can be further processed to recover lactose. In this case study, it is assumed that a nearby site has sufficient spare capacity in an existing lactose plant to process the concentrated permeate stream. Liquid volumes have already been reduced by the NF and RO polisher plants, so the concentrated WPC permeate can be transported without need for further processing.

The final, integrated process flowsheet for casein and WPC production is shown in Figure 7-46. Supporting mass balance calculations are presented in Appendix B.

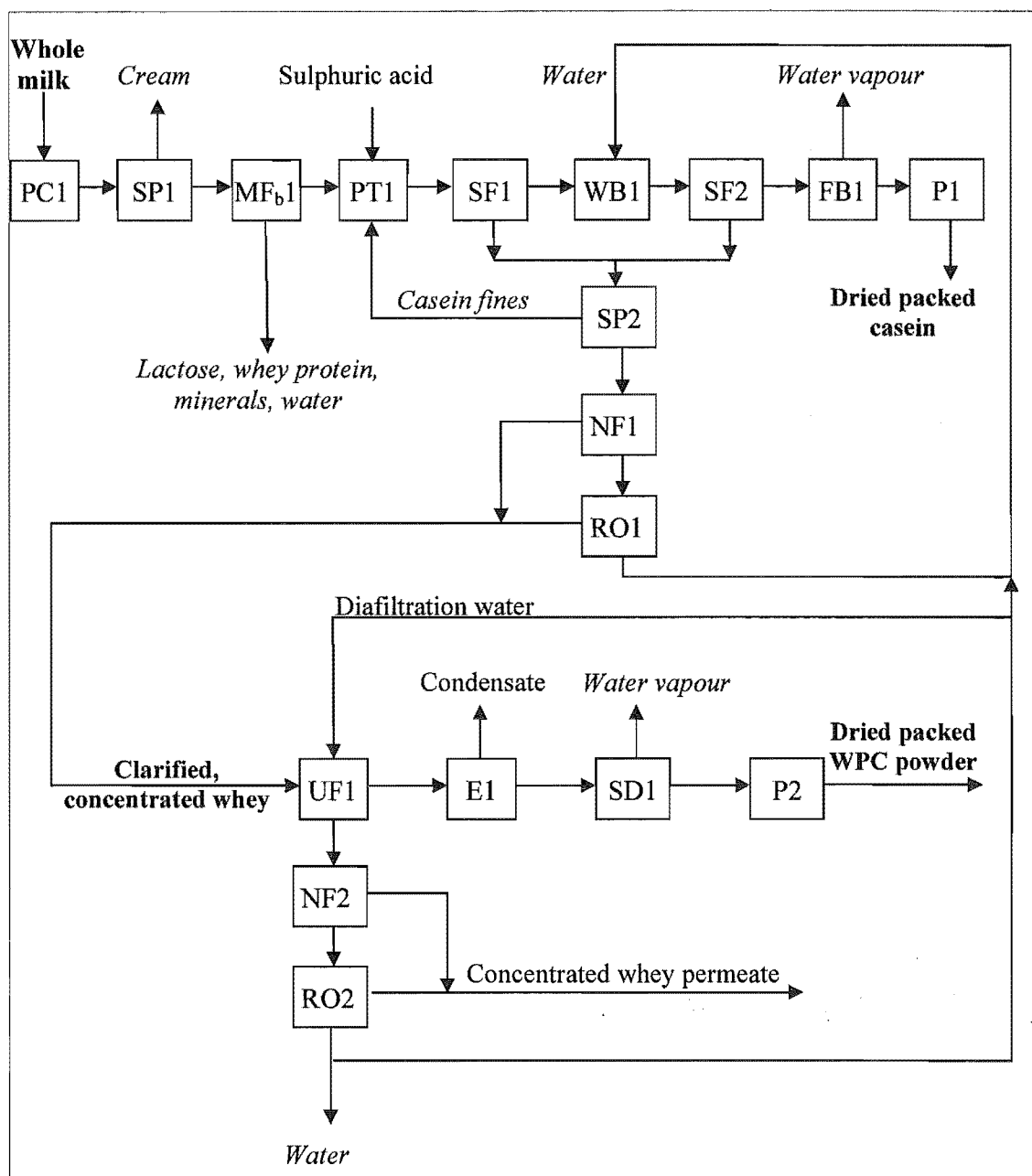


Figure 7-46 Integrated casein and WPC process flowsheet.

Table 7-26 shows input streams required for integrated casein and WPC flowsheet.

Table 7-26 Input streams required for integrated casein and WPC flowsheet.

Stream	Use	Flow rate [kg/hr]	Classification
Whole milk	Primary process feed	50000	Ingredient
Sulphuric acid	Injected into low fat milk to precipitate casein curd	20	Ingredient
Hot water	Used to heat curd to cooking temperature	9762	Utility

Table 7-27 shows output streams from the integrated casein and WPC flowsheet.

Table 7-27 Output streams from the integrated casein and WPC flowsheet.

Stream	Description	Source	Flow [kg/hr]	Classification
Casein	Packed casein powder	Packing line	1434	Primary product
Cream	High solids stream. Primarily fat, with small amounts of casein, whey protein, lactose and minerals.	Centrifugal separator processing whole milk feed	4796	Co-product
Skim milk permeate	Low solids stream. Contains lactose, whey protein and minerals.	Microfiltration plant processing skim from centrifugal separator	32348	Co-product
Whey protein concentrate	Packed WPC powder	Packing line	166	Co-product
Concentrated whey permeate	Medium solids stream containing mainly lactose and minerals	Combined retentate streams from NF and RO polisher plants processing WPC UF permeate	3309	Co-product
Warm water	Clean, warm utility water	Heating curd to cook temperature	9762	Utility
Demineralised water	Clean water with very low minerals content	Permeate from RO polisher processing NF retentate	2558	Co-product
Evaporator condensate	Water condensate with no solids	Evaporator processing ultrafiltration plant retentate	266	Utility
Water vapour	Water vapour	Hot exhaust gas from fluidised bed casein drier	4910	By-product
Water vapour	Water vapour	Hot exhaust gas from WPC spray drier	233	By-product

Casein production is a relatively complex design task, requiring several processing steps, and generating multiple co-product streams as a result. The conceptual design methodology provided a means to systematically generate and assess a variety of flow sheet alternatives. The final flowsheet generated by the design methodology was highly integrated, achieving an extensive amount of water recovery. The design tool provided a means to systematically identify and select integration options within and between process flowsheets.

7.4.3 Large Scale Milk Processing

Overview

Large-scale dairy process operations handle from 500,000 kg to 15 million kg of milk per day.

7.4.3.1 Case Study Four: Large Scale Milk Processing (Dried Packed Whole Milk Powder)

This case study illustrates the design methodology carried out in large scale dairy processing.

Design Methodology

Step 1: *Select the final product.*

The choice of product is based on the market demand and as an example, the product studied here is dry packed whole milk powder.

Step 2: *List the compositions of process feed and specifications of the final product.*

Feed = 2×10^6 kg raw whole milk per day.

The composition of feed, the product composition and specification are listed in Table 7-28.

**Table 7-28 Composition of feed, product composition and specification
(based on Walstra & Jenness, 1984; Walstra *et al.*, 1999).**

Components	Composition of feed ⁽¹⁾ [% w/w]		Composition of product ⁽²⁾ [% w/w]		Specification [% w/w]
	Wet basis	Dry basis	Wet basis	Dry basis	Wet basis
Fat	3.9	30.7	26	26.9	26 ± 1
Casein	2.6	20.5	19.5	20.2	> 24
Whey protein	0.65	5.1	4.9	5.1	
Lactose	4.6	36.2	38	39.4	---
Minerals and miscellaneous	0.95	7.5	8.1	8.4	---
Water	87.3	---	3.5	0	< 4
Total solids	12.7		96.5		96

⁽¹⁾ Typical liquid whole milk composition is based on Walstra & Jenness (1984).

⁽²⁾ Typical whole milk powder composition is based on Walstra *et al.* (1999).

Additional product specifications:

- The product needs to be flowable powder
- The product needs to dissolve and/or rehydrate easily

Step 3: *Calculate the mass flow of feed and product.*

Mass flow of feed = 2×10^6 kg raw whole milk per day

$$\text{Mass flow of product} = \text{Mass flow of feed} \times \frac{\% \text{ total solids in feed}}{\% \text{ total solids in product}} \quad (7-3)$$

$$= 2 \times 10^6 \text{ kg/day} \times \frac{12.7 \%}{96.5 \%}$$

$$= 263,212 \text{ kg/day of dry milk powder}$$

If 1 day = 24 production hours,

mass flow of product = $10,967 \text{ kg hr}^{-1}$ of dry milk powder

$$\approx 11 \text{ t hr}^{-1} \text{ of dry milk powder}$$

Step 4: *Compare the product composition with the feed to determine enrichment and/or depletion of components.*

Table 7-29 shows, from component calculations, that apart from water, fat is another component to be removed. On the other hand, lactose and minerals should be enriched. A detailed component mass balance can be found in Appendix C.

Table 7-29 The addition and removal of components.

Component	Enrichment [kg hr ⁻¹]	Depletion [kg hr ⁻¹]
Fat		361
Casein		0
Whey protein		0
Lactose	389	
Minerals and miscellaneous	108	
Water		72361

Step 5: *Select key process operation from Table 7-3 (based on Chapters 4 and 5).*

According to Table 7-3 and based on Section 5.5.1, the key process operation for the whole milk powder is spray drying. This is because spray drying can fulfil the additional product specifications listed in Step 2.

Step 6: *Define the scope of the key process operation from the feed to its product and relate the operation feed and product to the overall process feed and product.*

Designate a letter from Table 7-2 to the process.

Estimate the capital cost of the flowsheet and check its economic viability.

Processes to remove water are required to feed the spray drier (see Section 4.2.4). It may be necessary to further process the powder to achieved desired composition specification (Figure 7-47). A code is designated to the key process operation from Table 7-2.

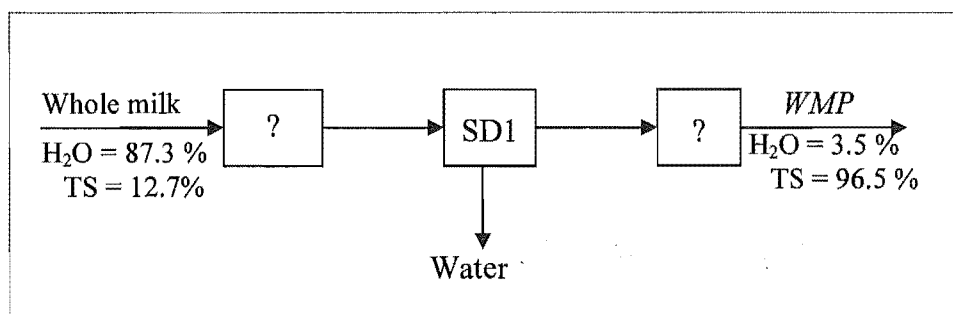


Figure 7-47 Process scope for production of whole milk powder.

Step 7: *Identify the requirements for the inputs, outputs and constraints of the selected key process operation (see Chapters 4 and 5). For the inputs, include composition calculations by approximate mass balance.*

Inputs: Feed has to be a concentrated liquid with total solids (TS) as high as possible (Figure 7-48). Spray driers are usually fed with liquid containing 45% to 50% total solids (see Section 4.2.4). The feed must be a pumpable liquid.

Outputs: Product is the whole milk powder with a moisture content of 2% to 10% (8% is used here).

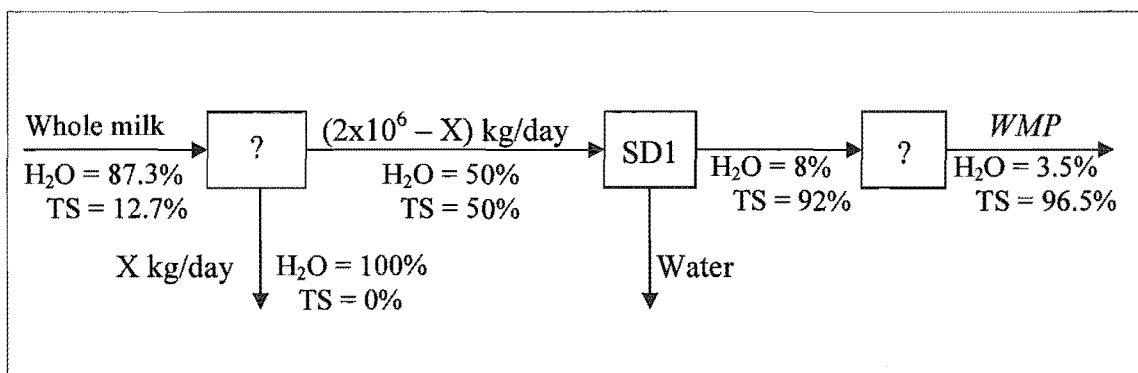


Figure 7-48 Input and outputs composition to key process.

The amount of water that must be removed prior to spray drying, (X in Figure 7-48) is computed to be 1.492×10^6 kg/day.

Step 8: Downstream processes:

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

If the last operation in the flowsheet does not produce the overall process product:

Find all operations that can process feeds the same as the current flowsheet product. For each of these:

If the new operation is feasible:

- *Give it an identification.*
- *Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.*
- *Calculate the component and overall mass flows for the main product and side products.*
- *Itemise utilities/effluents/timing.*
- *Estimate the capital cost of the flowsheet and check its economic viability.*
- *Call this step recursively.*

The first list of considerations contains the immediate processes after the key process operation. From Table 7-2, there are four options for taking the solid product from the spray drier and these are shown in Table 7-30.

Table 7-30 Downstream process options for operations after key process operation.

Process option	1 st consideration
Option 1	SD1-FB1
Option 2	SD1-DB1
Option 3	SD1-ST1
Option 4	SD1-P1

For Option 1, a fluidised bed drier is used to further dry the powder to the product specification. The use of a fluidised bed drier will allow a smaller and more efficient spray drier to be used, then would be the case if the spray drier did all the drying. The fluidised bed drier will dry the remaining moisture to meet the product specification (Walstra *et al.*, 1999). The advantages of fluidised bed driers include their low capital and maintenance costs, and their use for cooling. The resulting flowsheet is shown in Figure 7-48.

Fluidised bed drying can be used to coat the powder with lecithin to make instant milk powder (Bylund, 1995). The fluidised bed drier takes the solid key process products as a feed and dries this to the final dried product specification containing 96 % total solids. Therefore this option is considered to take the spray drier product as a feed.

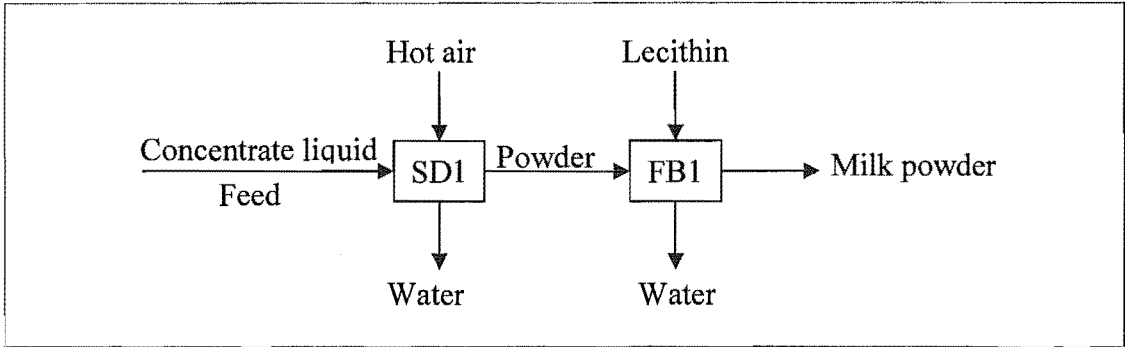


Figure 7-49 Spray drier integrated with fluidised bed drier.

For Option 2, dry blending would be a reasonable option if further components are to be added to meet the product composition shown in Figure 7-50. Dry blending could also be used to coat the powder with a liquid such as lecithin if this was not done in a fluidised bed drier.

Table 7-29 shows that whole milk powder needs lactose enrichment. Lactose enrichment can be achieved by dry blending (DB) of lactose and other ingredients such as minerals, skim milk powder or whole milk powder can be also added at this point.

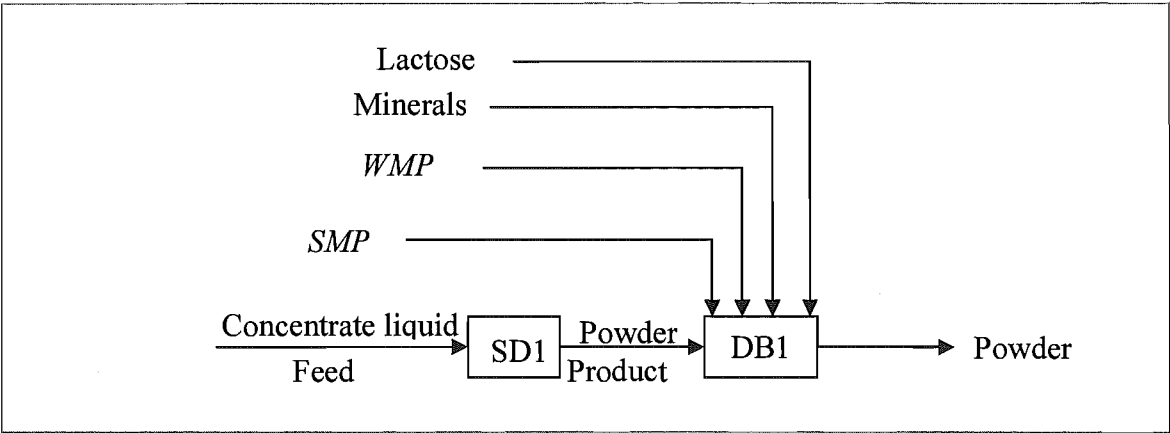


Figure 7-50 Spray drier integrated with dry blending.

Option 3, which considers direct storage of the product from the spray drying Figure 7-51. This would allow accumulation of powder for subsequent blending or packaging but the product might be too hot for storage.

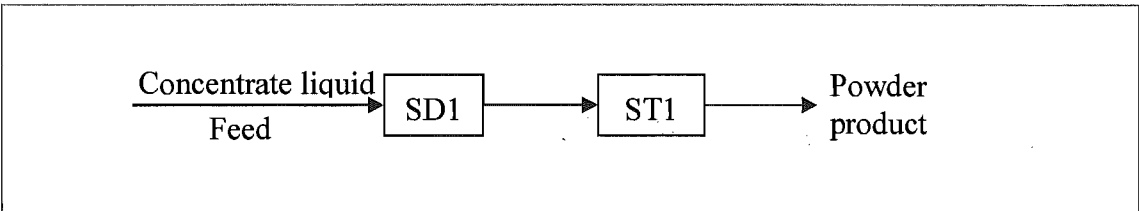


Figure 7-51 Storage integrated between spray drier and dry blending.

For Option 4, the product cannot be packed directly from the spray drier (Figure 7-52). As the product is too hot and may burn. Additional cooling by a conveying process (FB) would be required for this option to be considered.

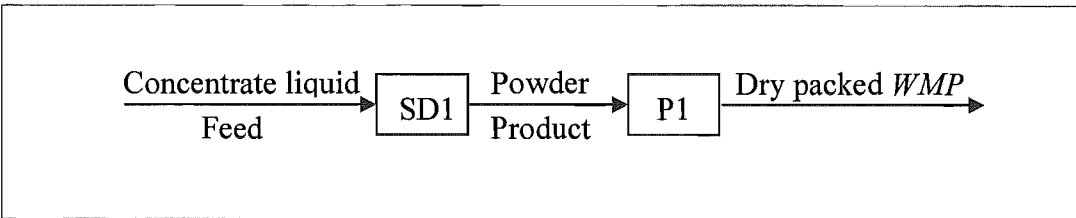


Figure 7-52 Spray drier integrated with packing.

Some of the possible process options derived from these immediate processes are listed in Table 7-31. This table shows a large number of possible alternatives. From all the available options, the most feasible ones are indicated with an asterisk (*). The options not considered further in this case study are indicated with strikeout. The Option considered not sensible are indicated with (^). Of these alternatives, the first choices are Options 1, fluidised bed dried (FB) and Option 2, dry blending (DB). These will be further considered.

Table 7-31 Possible downstream processes of the key process operation.

Process option	1 st Consideration	2 nd Consideration	3 rd Consideration
Option 1	SD1-FB1*	SD1-FB1-DB1*	SD1-FB1-DB1-ST1
			SD1-FB1-DB1-P1*
		SD1-FB1-P1*	
		SD1-FD1-ST1	
Option 2	SD1-DB1*	SD1-DB1-FB1	SD1-DB1-FB1-ST1
			SD1-DB1-FB1-P1
		SD1-DB1-ST1	SD1-DB1-ST1-FB1 [^]
			SD1-DB1-ST1-P1
		SD1-DB1-P1	
Option 3	SD1-ST1	SD1-ST1-DB1	
Option 4	SD1-P1		

The fluidised bed drier can be used prior to adding lactose into a dry blending as shown in Figure 7-53.

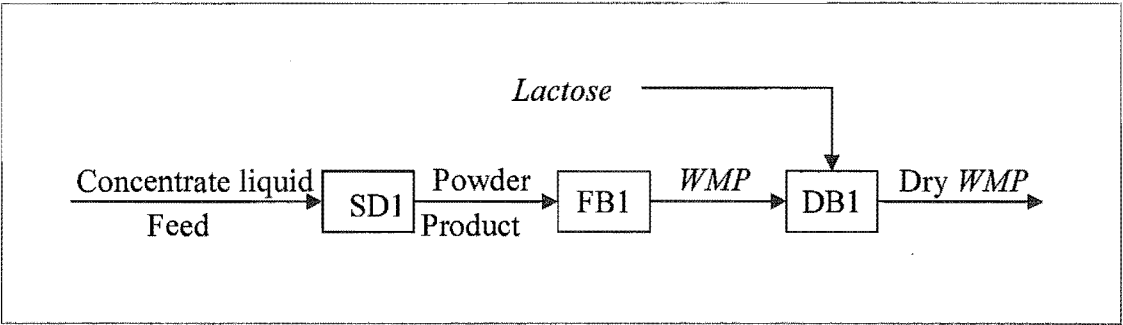


Figure 7-53 Production of the final product specification.

At this stage, the product composition has been met. Packing is required because the product specification is dry packed whole milk powder as shown in Figure 7-54.

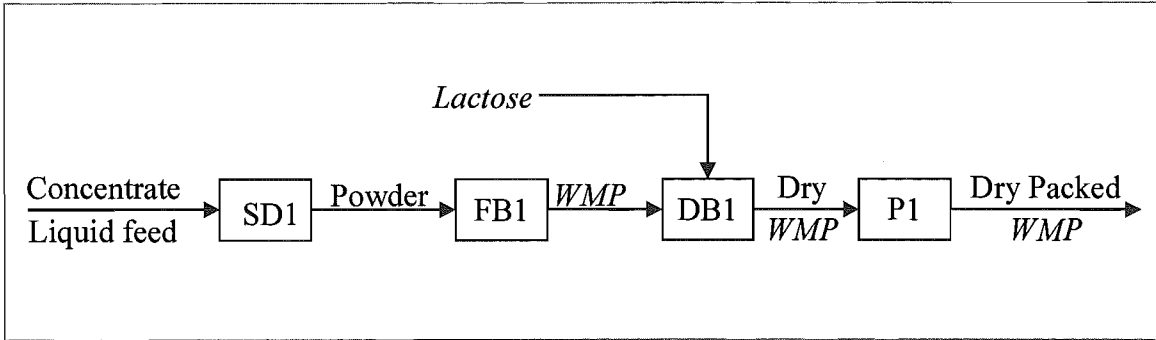


Figure 7-54 Dry blending integrated with packing to the required final product.

Table 7-32 summarises the utilities and emissions related to the key process operation; the code is given in Table 7-1.

Table 7-32 Utilities and emission requirements.

Code	Utilities required	Code	Emissions
st	steam		Condensate
el	electricity		
pw	15 °C	pw	15 °C
ha	150 °C - 250 °C	ma	80 °C
ca	15 °C		
	cleaning agents		cleaning agents

Step 9: *Upstream processes:*

(This is a recursive step). It will potentially give many different flowsheets with a combination of operations.

For each current flowsheet, do the following:

- If the first operation in the flowsheet is not fed by the overall process feed:*
- Find all operations that can produce the feed for the current flowsheet.*
- For each of these:*

If the new operation is feasible:

- *Give it an identification.*
- *Add it to the flowsheet under consideration and then add the flowsheet to the set of possible flowsheets.*
- *Calculate the component and overall mass flows for the main product and side products.*
- *Itemise utilities/effluents/timing.*
- *Estimate the capital cost of the flowsheet and check its economic viability.*
- *Call this step recursively.*

Spray driers are fed with liquid of 45% to 50% total solids content (see Section 4.2.4). There are various alternatives to produce milk concentrate. They are selected from Table 7-2 and shown here in Table 7-33.

Table 7-33 Water separation processes producing concentrate liquid.

Process option	1 st Consideration
Option 1	MF _b 1-SD1
Option 2	UF1-SD1
Option 3	NF1-SD1
Option 4	RO1-SD1
Option 5	WB1-SD1
Option 6	E1-SD1

From Table 7-33, the unit operations that concentrate liquid feed are examined in each option. These are then combined and further alternatives explored.

For Option 1 (Figure 7-55), tight microfiltration concentrates liquid by filtering out water, lactose, minerals and whey up to 13% total solids content (see Section 4.2.1.2). The concentrate is unlikely to meet the composition specification so this alternative is rejected.

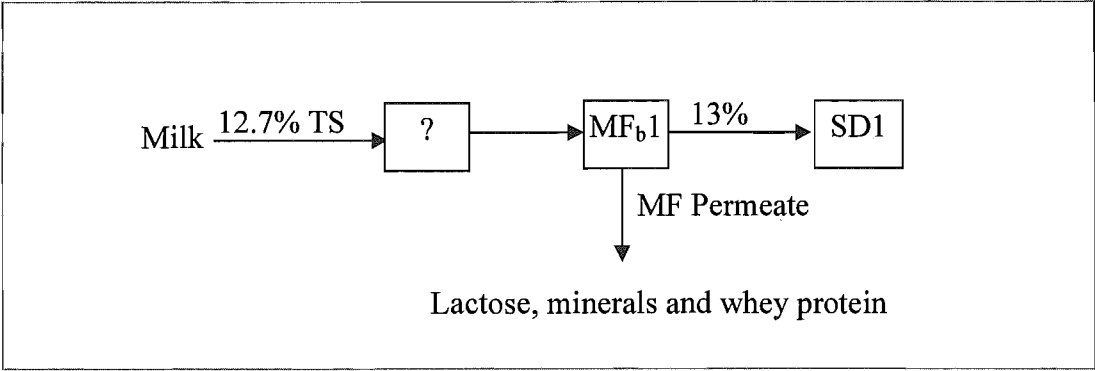


Figure 7-55 Microfiltration integrated with spray drier.

For Option 2 (Figure 7-56), ultrafiltration also concentrates liquid up to a maximum of 30% total solids (see Section 4.2.1.2). Again, the composition is unlikely to meet the specification as the lactose will be depleted and therefore this option is rejected.

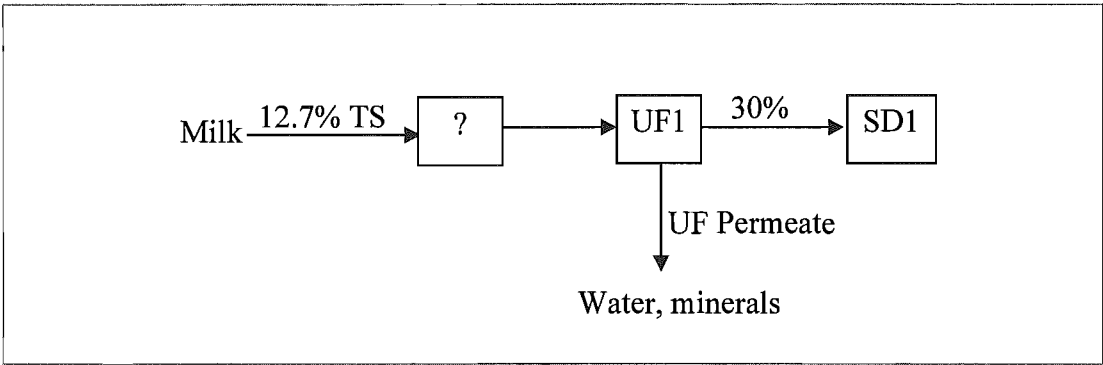


Figure 7-56 Ultrafiltration integrated with spray drier.

For Option 3 (Figure 7-57) nanofiltration concentrates the liquid to about 25% total solids (see Section 4.2.1.2). Both the low total solids level and mineral depletion make this process unsuitable here.

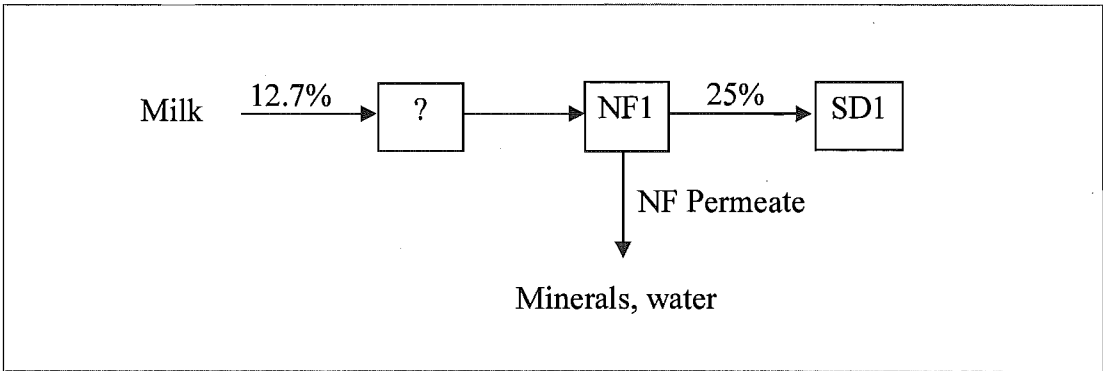


Figure 7-57 Nanofiltration. integrated with spray drier.

For Option 4 (Figure 7-58) reverse osmosis can be used to remove water from the milk to produce a concentrated liquid product (see Section 4.2.1.2). However, the maximum concentration of 21% TS is insufficient as a direct feed to the spray drier.

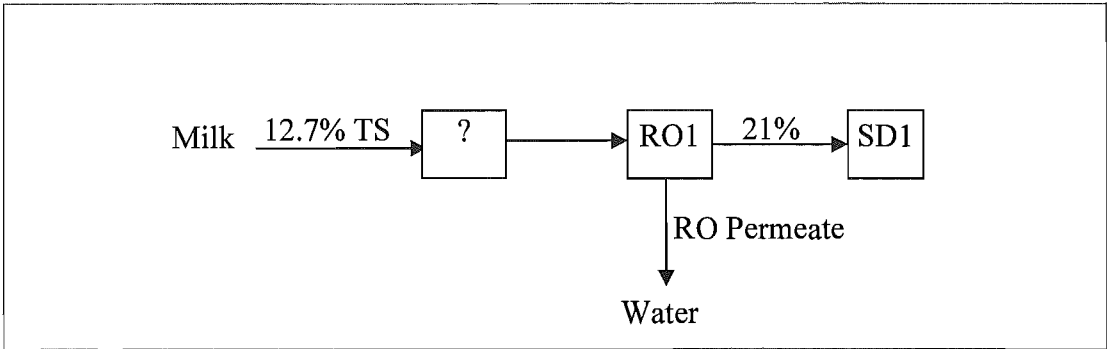


Figure 7-58 Reverse osmosis integrated with spray drier.

For Option 5 (Figure 7-59) wet blending is considered (see Section 4.3). The spray drier feed can be generated by wet blending different ingredients into the milk stream. It may be necessary to concentrate the milk upstream of wet blending, to ensure the drier receives a feed stream with 50% total solids.

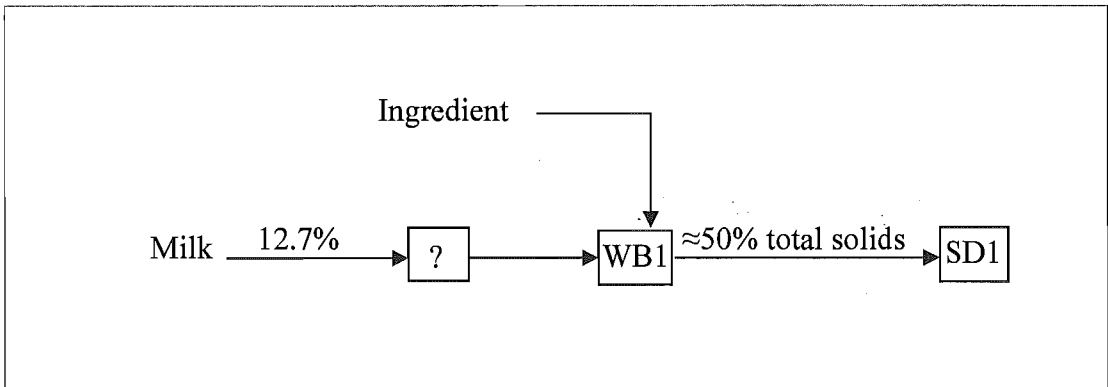


Figure 7-59 Wet blending integrated with spray drier.

For Option 6 (Figure 7-60) the solids content of milk can be increased by the removal of water by evaporation under vacuum. Water removal by evaporation requires less energy than by drying (see Table 4-4). The evaporator concentrates liquid milk up to 45% to 50% TS (see Section 4.2.3). This is a very suitable process alternative.

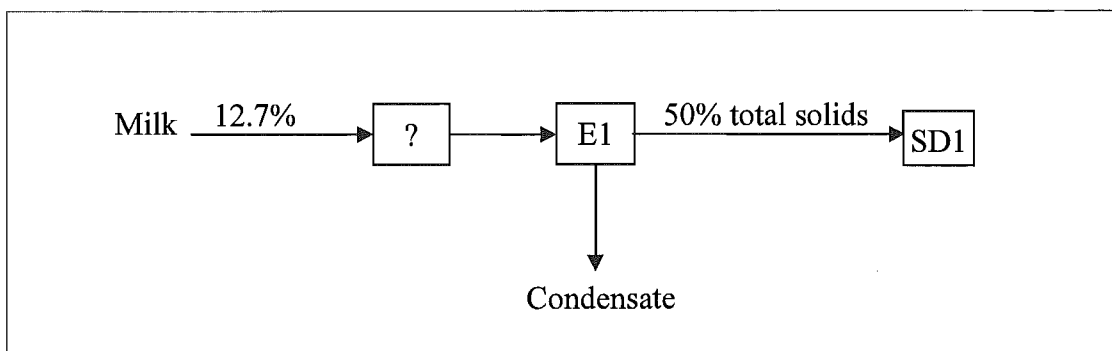


Figure 7-60 Evaporation integrated with spray drier.

Table 7-34 summarises the alternatives from which Options 5 and 6 are the only two that seem feasible. Options 1 to 4 are rejected since they are unable to achieve a drier feed stream with 50% total solids.

Table 7-34 Identification of upstream alternatives to produce feed into the key process operation.

Option	Supplies that concentrate liquids	Product TS %	Water Removal t/hr.	Feed to key process operation
Option 1	MF	13	1.9	No
Option 2	UF	30	48	No
Option 3	NF	25	41	No
Option 4	RO	21	32.9	No
Option 5	WB	50	---	Yes
Option 6	E	50	62.1	Yes

Option 5 offers the ability to manipulate the product composition, but requires a feed stream with elevated total solids concentration. Option 6 offers a suitable means to generate a concentrated milk stream. Therefore, both Option 5 and 6 are selected to jointly generate the drier feed stream, as shown in Figure 7-61.

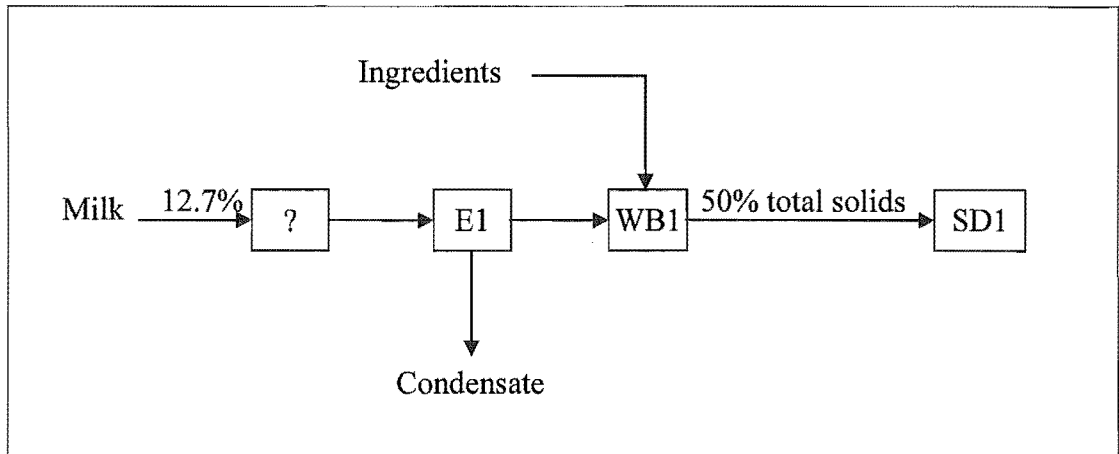


Figure 7-61 Evaporation and wet blending integrated with spray drier.

Feed alternatives for the wet blending process are potentially any source of casein, fat, whey protein, minerals and water combined. For example:

1. Concentrated liquid permeate, cream, lactose in concentrate solution and caseinate in solution. A homogeniser would be required before the spray drier.
2. Skim milk concentrate, cream, concentrated lactose solution. A homogeniser would be required before the spray drier.
3. Caseinate, whey protein concentrate, lactose 65% in solution, AMF and minerals with pH adjustment. However, additional mixing equipment will be necessary.

From these three feeds, feed alternative 2 seems the most sensible option to be considered although feed alternatives 1 and 3 theoretically seem to meet the feed composition.

There are several alternatives for milk components to be fed to the evaporator. Five options are showing in Table 7-35.

Table 7-35 Possible feed options to evaporation process.

From process	1 st	2 nd	3 rd
Option Six	Consideration	Consideration	Consideration
Option 1	MF1	E1-WB1-SD1	MF1-E1-WB1-SD1
Option 2	UF1	E1-WB1-SD1	UF1-E1-WB1-SD1
Option 3	NF1	E1-WB1-SD1	NF1-E1-WB1-SD1
Option 4	RO1	E1-WB1-SD1	RO1-E1-WB1-SD1*
Option 5	SP1	E1-WB1-SD1	SP1-E1-WB1-SD1*

For Option 1 (Figure 7-62), microfiltration can be used to remove fat and micro-organisms. This options is rejected because microfiltration also depletes whey protein, lactose and minerals that are required for the product.

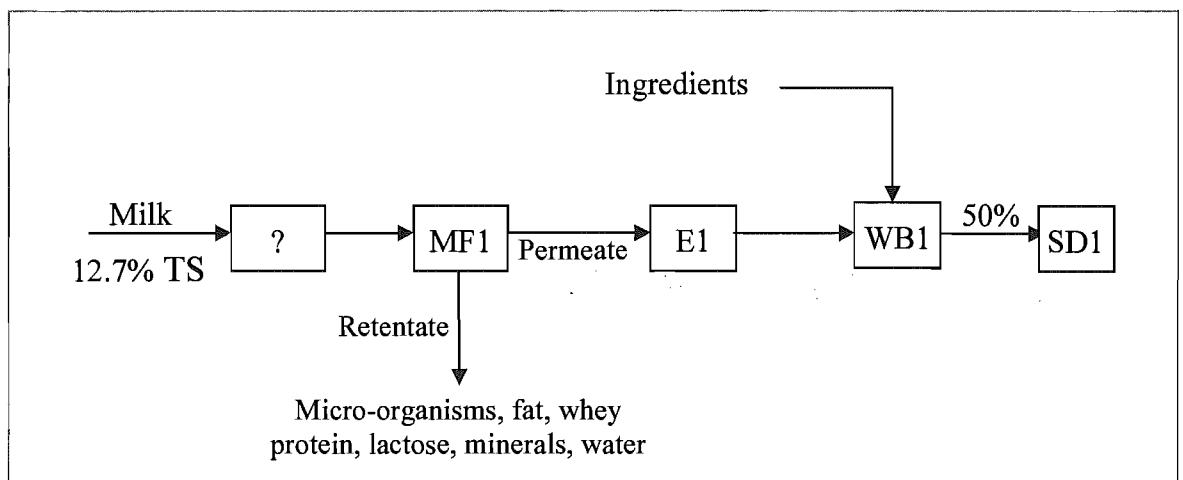


Figure 7-62 Microfiltration of evaporator feed prior to wet blending and spray drying,

For Option 2 (Figure 7-63), ultrafiltration can be used to concentrate a liquid milk up to 30% TS. It will produce milk rich in proteins, but depleted in lactose and minerals that are needed for the product. Therefore, this option is rejected.

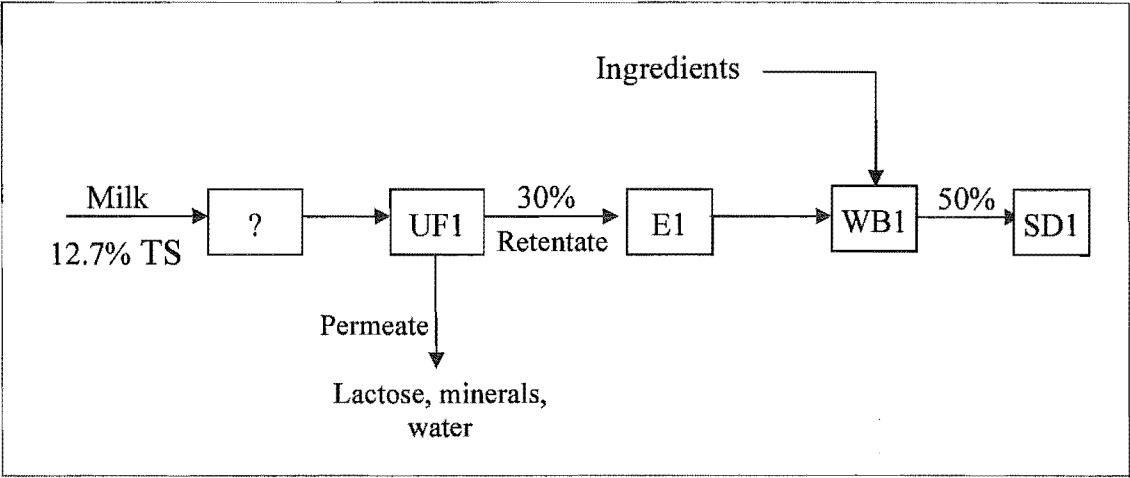


Figure 7-63 Ultrafiltration of evaporator feed prior to wet blending and spray drying.

For Option 3 (Figure 7-64) nanofiltration can be used to concentrate the liquid to 25% totals solids. However this process option is rejected because it depletes minerals that are needed for the product.

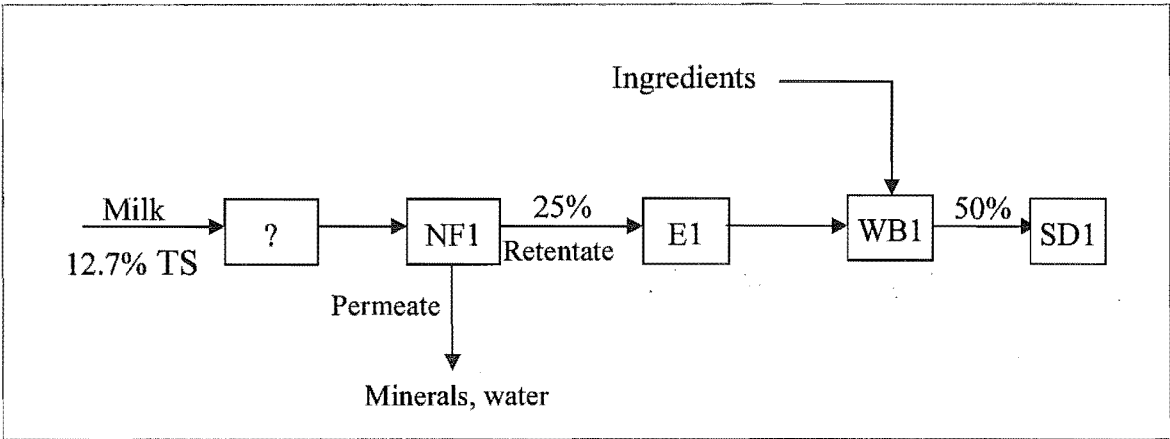


Figure 7-64 Nanofiltration of evaporator feed prior to wet blending and spray drying.

For Option 4 (Figure 7-65), RO is used to reduce the water content in the feed to the evaporator. This produces a water stream which can be utilised elsewhere in the process. This option is highly desirable since it does not deplete any solids component of interest, and removes water more efficiently than an evaporator.

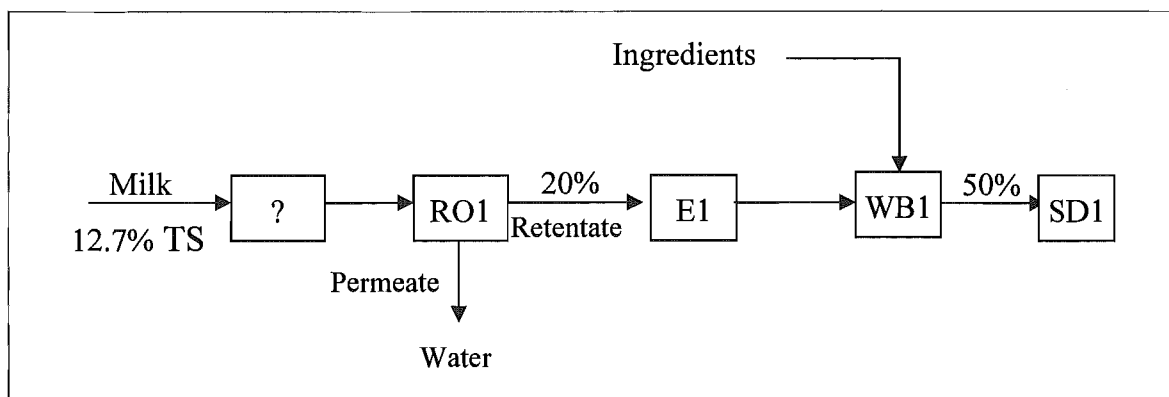


Figure 7-65 Reverse osmosis of evaporator feed prior to wet blending and spray drying.

For Option 5 (Figure 7-66), a centrifugal separator is used to remove fat from the whole milk feed. This is desirable, since fat depletion is necessary to achieve the desired product specification (Table 7-29). The separator may either process a small proportion of the whole milk (since only as small amount of fat depletion is required), or process all whole milk feed with subsequent wet blending of cream to achieve the desired product composition.

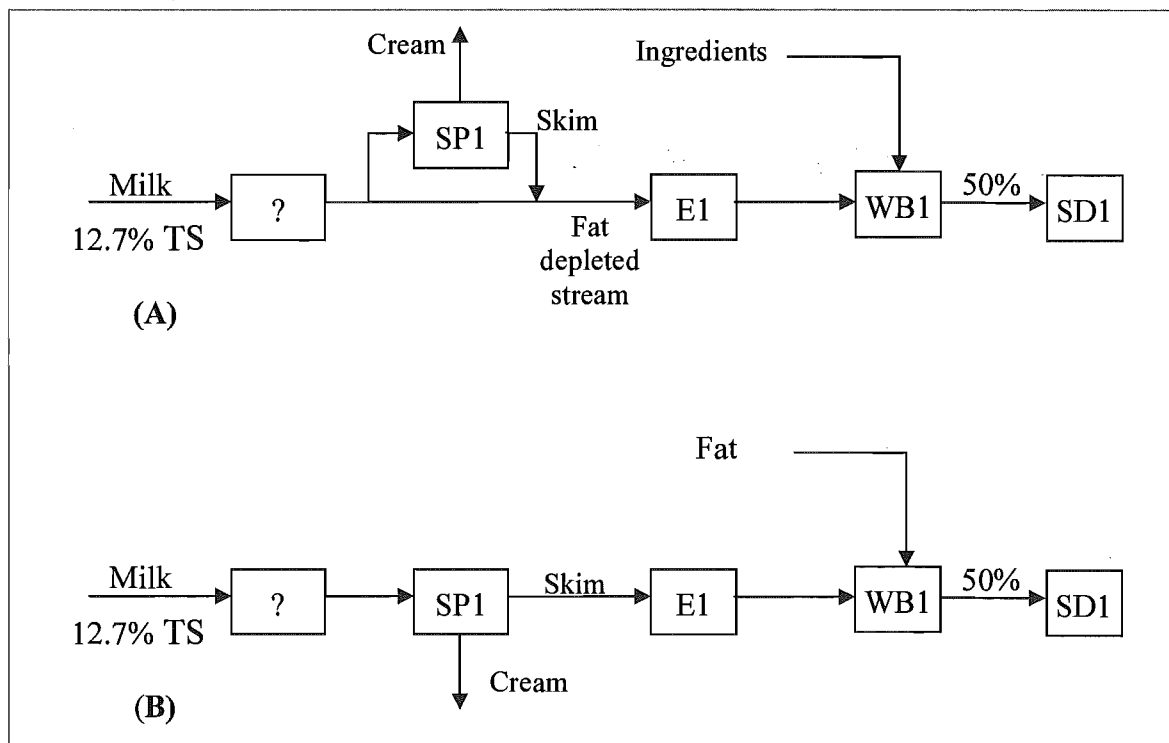


Figure 7-66 Centrifugal separator generating skim feed to evaporator (A) or depleted fat feed to evaporator (B), prior to wet blending and spray drying.

Both Options 4 and 5 are desirable. Option 5 is necessary, to achieve the required fat depletion. Centrifugal separation of the entire whole milk stream (Figure 7-66B) reduces the liquid volume passing through the evaporator. Fat can be wet blended back onto the evaporator concentrate prior to the spray drier. Fat can either be supplied using cream or AMF ingredient. Given the availability of cream this is chosen as the prefer ingredient. Option 4 further reduces the liquid volume passing through the evaporator by raising the evaporator feed solids concentration. Food safety and longer shelf life demand that milk flowsheets should also include pathogen control (see Sections 4.1 and 4.8). The final, linear process flowsheet including pathogen control is shown in Figure 7-67.

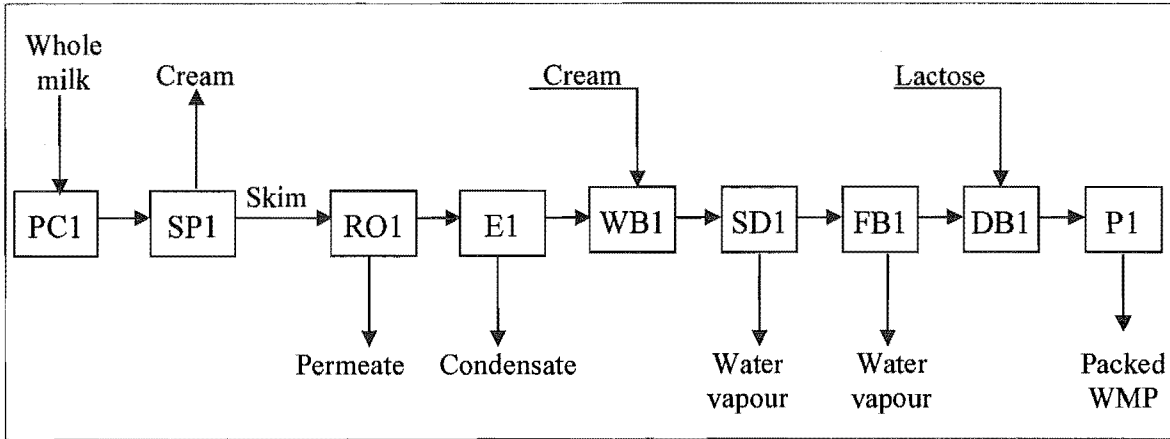


Figure 7-67 Final linear flowsheet of packed dried whole milk powder.

Step 10: *Check for each side products from the linear flowsheet. Classify them as co-products, by-products and waste products (see Section 3.3).*

Table 7-36 shows the input streams required for the milk powder flowsheet developed in Step 9. Calculations for this case study are presented in Appendix C.

Table 7-36 Input streams for the milk powder flowsheet.

Stream	Use	Flow [kg/hr]	Classification
Whole milk	Primary process feed	83333	Ingredient
Lactose powder	Dry blended into dry powder from fluidised bed drier to attain desired product composition	700	Ingredient

Table 7-37 shows the output streams from the milk powder flowsheet developed in Step 9. Calculations for this case study are presented in Appendix C.

Table 7-37 Output streams from the milk powder flowsheet.

Stream	Description	Source	Flow [kg/hr]	Classification
Whole milk powder	Packed whole milk powder	Packing line	11028	Primary product
Cream	High solids stream. Primarily fat, with small amounts of casein, whey protein, lactose and minerals.	Centrifugal separator processing whole milk feed	955	Co-product
Evaporator condensate	Water condensate with no solids	Evaporator processing skim RO retentate	24759	Utility
RO permeate	Clean water containing very low concentrations of minerals	Skim RO plant feeding evaporator	37677	Co-product
Water vapour	Water vapour	Hot exhaust gas from spray drier	9081	By-product
Water vapour	Water vapour	Hot exhaust gas from fluidised bed drier	505	By-product

Step 11: *If it is a co-product, treat it as a new feed to the further processing and repeat the design methodology from Step 1.*

There are two possible co-product streams produced by the proposed milk powder flowsheet shown in Figure 7-67, and summarised in Tables 7-36 & 7-37. Cream is a co-product that has immediate value without any further processing; it may be sent to another factory on site, or on-sold to another processor. In this case study it is assumed that cream is sent to another factory for processing. RO permeate cannot be manufactured into a saleable dairy product, but is still considered to be a valuable co-product since it can be used in place of potable water.

Step 12: *If it is a by-product or waste product, look for opportunities to off-set cost of discharging otherwise determine a suitable treatment for its disposal.*

The only by-product identified in Table 7-37 is water vapour from the spray and fluidised driers. Discharging this does not have any associated costs.

Step 13: *Identify the matching streams within the flowsheet. Consider products and equipment constraints. Check for energy, water, time and environmental integration opportunities.*

The RO permeate stream (Table 7-37) is not formally matched within the flowsheet, however this water is valuable, and will be used within the process, most likely for CIPs (see Section 6.3.5).

Step 14: *Identify the matching product between flowsheets (linear flowsheet and the new co-product processing flowsheets). Check for energy, water, time and environmental integration opportunities.*

With no co-products selected for further processing in this case study, there are no other flowsheets to integrate with. Had the cream co-product been further processed, integration with an AMF or butter process may have been necessary. Because milk powder production is primarily based on water removal, milk powder plants tend to be stand-alone processes.

Step 15: *If the co-product cannot be processed due to the capacity problem, it may be necessary to identify the proximity matching product between sites .*

Not applicable for this case study.

Application of the conceptual design methodology to large scale milk powder production produced an innovative flowsheet that is substantially different to 'typical' milk powder plants. This case study illustrated the ability of the methodology to systematically generate and assess a variety of flowsheet options. This tool ultimately developed a novel but feasible flowsheet that satisfied the specified product and production requirements.

8 Conclusions

This thesis aimed to develop a conceptual methodology for the design of dairy processes so as to enable design information for a designer's innovative design in dairy processing. Analysis of design methodologies published in literature has demonstrated that dairy process design is very different from others, particularly the petrochemical industry. Dairy process design deserves a unique methodology since none of the existing standard design methods are applicable.

There are notable differences between dairy processes and traditional chemical engineering processes. Solid and liquid separations and mixing are commonly used in dairy industry while in traditional chemical industry, reactors are the main unit operation.

In addition, dairy processes are different because of the raw material push, the perishable nature of milk and food safety. Product recycling is limited by many constraints and there are large changes in milk supply volumes throughput during the season. It was necessary to explore the main uses of milk in the industry to determine the process characteristics of the products together with the constraints imposed on the design. For this reason, the development of schematic flowsheets in each product was useful.

It was found that each product has a key process that cannot be avoided in the process flowsheet. This key process concept provides the starting point of a large number of potential design alternatives.

When reviewing current dairy processes it was found that the principles of operation normally discussed in textbooks could not be used immediately for design. For each operation a different design point of view was required to show essential design information including objectives and constraints.

It was found that large scale dairy processes have more opportunities for integration and more product alternatives than small scale dairy processing. These characteristics play a significant role in determining the numerous opportunities for integration which improve recovery and or recycle of several streams and water conservation. Simplified examples of integration have been identified, between and within processes in the same site and between sites.

This analysis was used to develop a new conceptual design methodology tailored specifically to dairy processes. The methodology provides a mean for selecting preferred flowsheeting options.

The methodology includes the possibility of generating partial solutions means by reducing and creating sets of processes downstream and upstream of the key process, thus minimising the number of options that have to be managed. The design methodology presents a synthesis technique for generating design alternative flowsheets upstream and downstream from the key process operation.

The methodology integrates the idea of screening unit operations via feed and products requirements and additional information of product specifications. Screening is an important enhancement of the technique for design dairy processes synthesis problem, which are often characterised by a large number of milk components and a wide selection of unit operations. The design analysis reduces the size of the design space and options for enhancing the diversity of the flowsheet are generated.

It has been shown that a methodology can be constructed that is suitable for a range of scales, that encourages lateral innovative thoughts. The conceptual design methodology developed was tested for a variety of scales and products in four case studies. Case studies were used to illustrate the application of this methodology to different situations. The methodology was successfully applied to small, medium and large scale sites. From the case studies it was found that there are strong similarities between different dairy processes. These tests suggest that the design methodology developed here describes well the procedure to design dairy processes.

The method proposed in this thesis allows a chemical engineer to design a dairy process industry. This methodology is applicable to a chemical process in the early stages of process design for which some knowledge of anticipated chemical engineering background is needed. The methodology also allows the chemical process engineer to measure the performance of different alternatives at different scales and produce designs which minimise the effluents and increase the product yield thus maximizing the plant operation and therefore giving the highest return to the farmers/shareholders. The steps of the methodology are general enough for application beyond the case studies presented. The methodology provides basic insight into potential process integration options for product, co-product, energy, water, time and the environment.

From the generalised process descriptions and schematics, it was possible to generate a number of potential flowsheet alternatives for the case studies.

The benefit of this methodology is the creativity arising from the use of a “top down” approach and the availability of a wide range of alternatives. These advantages prove the methodology to be an extremely valuable tool to an engineer when designing dairy processes.

Recommended Future Work

From the investigation presented in this thesis, it is believed that this methodology can be further improved by refining the economic analysis. It is also highly desirable to incorporate product selection within a flowsheet design methodology based on the economic analysis. This can be extended to include better economic analysis that takes into account of the labour, energy and utilities.

In this work, technical feasibility rather than economics was used to select the potential designs. The real need is, when selecting the key process, that the required capital cost should be compared with the maximum net revenue from product. When adding a process to the key process, the accumulated capital cost must be compared. If the total flowsheet cost exceeds the maximum capital expenditure allowed, then the new process will be rejected. An example is demonstrated for Case Study Two. It must be noted that cost is a rejection criteria and it is not a selection (ranking) criteria.

Incorporating the energy and water integration methodology of French (2003) into this conceptual methodology is advisable to enhance the completeness of the integration opportunities. The scope can be enlarged to include other integrations such as the time integration and component integration.

The time integration to be included in the methodology is expected to involve the optimisation of plant utilisation throughput through the season.

The component integration can be further studied by considering the composition variations through the season.

This methodology has the potential to be translated into an engineering design software tool. This effort is expected to quicken the filtering of design alternatives and increase the accessibility of this methodology to more process design engineers. For this reason, it is recommended that further work be focussed in this area.

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Appendix A – Case Study Two

Small scale milk processing: Packed Cottage Cheese

APPENDIX A: Case study two**Small scale milk processing: Packed Cottage cheese*****A comparison of wet basis composition of product to raw milk feed in order to determine required component enrichment / depletion***

The following calculations show how the mass balance is calculated for steps 3 and 4 of the methodology

Assume that 1 day = 8 production hours.

Feed and product composition based on Spreer (1998) and Kessler (1981).

Overall casein yield = 95 %

	Raw milk (feed)		Cottage cheese		(Product - Feed)		
Mass flow [kg/d]	5000		1004.1		-3995.9		
Mass flow [kg/hr]	625.0		125.5		-499.5		
	% w/w	kg/hr	% w/w	kg/hr	% w/w	kg/hr	
Fat	3.9	24.4	4.3	5.4	3.8	-19.0	<p>Large negative value for fat means that there are excessive amounts of fat in the feed stream. An upstream process must be used to generate a low-fat feed stream</p>
Casein	2.6	16.3	12.3	15.4	0.2	-0.8	
Whey Protein	0.65	4.1	0.5	0.6	0.7	-3.4	
Lactose	4.6	28.8	2.0	2.5	5.3	-26.2	
Minerals & miscellaneous	0.95	5.9	1.0	1.3	0.9	-4.7	
Water	87.3	545.6	78.0	97.9	89.6	-447.7	
Salt	0.0	0.0	1.9	2.4	-0.5	2.4	
Coagulant	0.0	0.0	0.0	0.0	0.0	0.0	
Total Solids, TS	12.7	79.4	22.0	27.6	10.4	-51.8	

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the % yield of casein
- 4) Calculate the flowrate of casein in the product where it is = (flowrate of casein in feed) * (% yield of casein)
- 5) List the required composition of product
- 6) Calculate the total flowrate of product stream where it is = (flowrate of casein in product) / (% of casein in product)
- 7) Calculate the flowrate of other total solids and water in the product stream
- 8) Determine the difference in flowrate of each component between the product and feed i.e. (Product - Feed)
- 9) For each component, a negative value of (Product - Feed) means that component need depletion while a positive value means enrichment
- 10) Determine the composition of each component in (Product - Feed)

APPENDIX A: Case study two

Small scale milk processing: Packed Cottage cheese

Component balance over centrifugal separator used to remove fat from feed stream prior to cottage cheese production

The following calculations show how the mass balance is calculated for Step 8 of the methodology

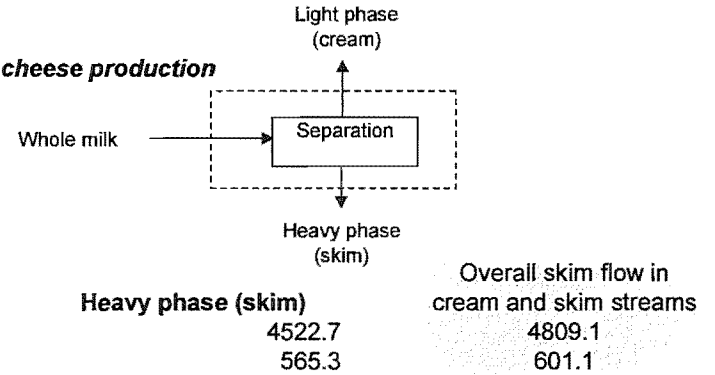
Assume that 1 day = 8 production hours.

Feed composition based on Spreer (1998).

Assumed skim fat concentration = 0.09 % (hot separation, Bylund, 1995)

Assumed cream fat concentration = 40 % (Bylund, 1995)

Assume cream is a mixed stream of fat and skim



Raw milk (feed)			Light phase (cream)		Heavy phase (skim)		Overall skim flow in cream and skim streams
Mass flow [kg/d]							
Mass flow [kg/hr]							
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	
Fat	3.9	24.4	40.0	23.9	0.09	0.5	
Casein	2.6	16.3	1.6	1.0	2.7	15.3	
Whey Protein	0.65	4.1	0.4	0.2	0.7	3.8	
Lactose	4.6	28.8	2.9	1.7	4.8	27.0	
Minerals & miscellaneous	0.95	5.9	0.6	0.4	1.0	5.6	
Water	87.3	545.6	54.5	32.5	90.8	513.1	
Salt	0.0	0.0	0.0	0.0	0.0	0.0	
Coagulant	0.0	0.0	0.0	0.0	0.0	0.0	
Total Solids, TS	12.7	79.4	45.5	27.1	9.2	52.2	

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the % fat in cream
- 4) Specify the % fat in skim milk
- 5) Calculate the heavy phase flow rate, using fat as the tie-stream = $\text{feed flowrate} \times (\% \text{ feed fat} - \% \text{ cream fat}) / (\% \text{ skim fat} - \% \text{ cream fat})$
- 6) Calculate the total flowrate of skim milk in light and heavy phases
- 7) Calculate the concentrations of other components in heavy phase using feed compositions and total skim flow rate
- 8) Determine the component flows in light phase by difference from feed and heavy streams
- 9) Calculate component concentrations in light phase using component flows and total light phase flow rate

APPENDIX A: Case study two**Small scale milk processing: Packed Cottage cheese*****Component balance over precipitation***

The following calculations show how the mass balance is calculated for Step 8 of the methodology - key process (precipitation)

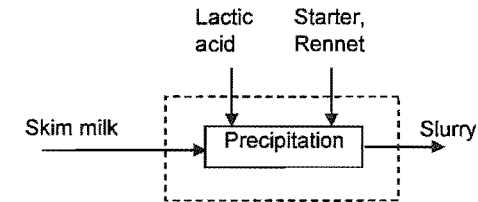
Assume that 1 day = 8 production hours.

Feed is skim milk from separator

Lactic feed acid concentration = 10 %

Lactic acid dosing rate 12.5 kg/hr

Starter, rennet dosing = 2.0 ml/1000kg (insignificant)



	Skim milk (feed)		Coagulant (lactic acid)		Slurry	
Mass flow [kg/d]	4522.7		100.0		4622.7	
Mass flow [kg/hr]	565.3		12.5		577.8	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.09	0.5	0.0	0.0	0.1	0.5
Casein	2.7	15.3	0.0	0.0	2.6	15.3
Whey protein	0.7	3.8	0.0	0.0	0.7	3.8
Lactose	4.8	27.0	0.0	0.0	4.7	27.0
Minerals & Miscellaneous	1.0	5.6	0.0	0.0	1.0	5.6
Water	90.8	513.1	90.0	11.3	90.7	524.4
Salt	0.0	0.0	0.0	0.0	0.0	0.0
Coagulant	0.0	0.0	10.0	1.3	0.2	1.3
Total Solids, TS	9.2	52.2	10.0	1.3	9.3	53.5

Calculation steps

- 1) List the composition of skim and coagulant streams
- 2) Determine the flowrate of each component in the skim and coagulant streams
- 3) Calculate component and overall mass flows in slurry by summation of skim and coagulant flows
- 4) Calculate component concentrations in slurry from component and overall mass flows

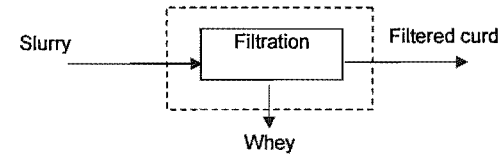
APPENDIX A: Case study two**Small scale milk processing: Packed Cottage cheese****Component balance over slurry filtration**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - curd slurry filtration

Assume that 1 day = 8 production hours.

Feed is cheese curd

Curd water content =	82.3 %
Fat yield in curd =	90 %
Casein yield in curd =	99 %
Whey protein yield in curd =	15 %
Lactose yield in curd =	8 %
Minerals yield in curd =	20 %
Coagulant yield in curd =	0 %



	Slurry		Whey		Filtered curd	
Mass flow [kg/d]	4622.7		3744.0		878.7	
Mass flow [kg/hr]	577.8		468.00		109.8	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.1	0.5	0.0	0.1	0.4	0.5
Casein	2.6	15.3	0.0	0.2	13.8	15.1
Whey protein	0.7	3.8	0.7	3.2	0.5	0.6
Lactose	4.7	27.0	5.3	24.9	2.0	2.2
Minerals & Miscellaneous	1.0	5.6	1.0	4.5	1.0	1.1
Water	90.7	524.4	92.7	434.0	82.3	90.4
Salt	0.0	0.0	0.0	0.0	0.0	0.0
Coagulant	0.2	1.3	0.3	1.3	0.0	0.0
Total Solids, TS	9.3	53.5	7.3	34.0	17.7	19.4

Calculation steps

- 1) List the composition of slurry stream
- 2) Determine the flowrate of each component in the slurry stream
- 3) Calculate component mass flows in filtered curd from assumed yield values
- 4) Calculate the total mass flow rate of filtered curd using moisture as a tie-stream

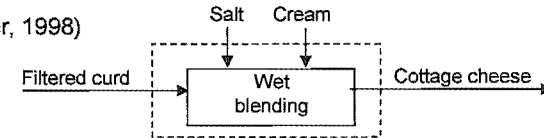
$$= (\text{sum all non-water component flows in filtered curd stream}) / (1 - \% \text{ water in filtered curd} / 100)$$
- 5) Calculate water mass flow from specified % concentration and overall mass flow of filtered curd
- 6) Calculate component and overall mass flows in whey by difference
- 7) Calculate % component concentrations in whey stream from mass flows

APPENDIX A: Case study two**Small scale milk processing: Packed Cottage cheese****Component balance over wet blending**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - wet blending of filtered curd

Assume that 1 day = 8 production hours.

Cream, salt and water added to get desired product composition (based on Spreer, 1998)



	Filtered curd		Salt		Cream (light phase)		Cottage cheese		Desired product
Mass flow [kg/d]	878.7		19.2		99.2		997.1		(Spreer, 1998)
Mass flow [kg/hr]	109.8		2.4		12.4		124.6		(Kessler, 1981)
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]
Fat	0.4	0.5	0.0	0.0	40.0	5.0	4.3	5.4	4.3
Casein	13.8	15.1	0.0	0.0	1.6	0.2	12.3	15.3	12.3
Whey protein	0.5	0.6	0.0	0.0	0.4	0.1	0.5	0.6	0.5
Lactose	2.0	2.2	0.0	0.0	2.9	0.4	2.0	2.5	2.0
Minerals & Miscellaneous	1.0	1.1	0.0	0.0	0.6	0.1	1.0	1.2	1.0
Water	82.3	90.4	0.0	0.0	54.5	6.8	77.9	97.1	78.0
Salt	0.0	0.0	100.0	2.4	0.0	0.0	1.9	2.4	1.9
Coagulant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Solids, TS	17.7	19.4	100.0	2.4	45.5	5.6	22.0	27.5	22.0

Calculation steps

- 1) List the composition of filtered curd stream
- 2) Determine the flowrate of each component in the filtered curd stream
- 3) Specify component concentrations in salt and water streams
- 4) Use same component concentrations for skim stream as calculated in whole milk separator mass balance (A-2)
- 5) Estimate initial mass flow rates for salt, water and skim streams
- 6) Calculate the total mass flow rate of filtered curd using moisture as a tie-stream
- 7) Calculate component mass flows for salt, water and skim streams
- 8) Calculate component mass flows in final product by summation of component mass flows in ingredient streams
- 9) Calculate overall mass flows of final product by summation of overall mass flows in ingredient streams
- 10) Calculate component concentrations in final product from component mass flows and total stream flow rate
- 11) Refine estimated salt, water and skim stream flow rates until final product compositions equal desired values

Case Study Two: Small scale milk processing (packed cottage cheese)**Economic analysis of the cottage cheese production in regard to the key process:**

Feed	[kg/day]	5000
% casein in feed	[%]	2.6
% yield of casein in process	[%]	95
% casein in product	[%]	12.3
Cottage cheese production rate	[kg/day]	1004

Working days / year	[day]	200
Value of product	[US\$/kg]	5.6
Total value of product	[US\$/year]	1130979

$$\text{Total value of product} = \left(\frac{\text{Cottage cheese}}{\text{production rate}} \right) \times \left(\frac{\text{Working days}}{\text{per year}} \right) \times \left(\frac{\text{Value of}}{\text{product}} \right)$$

Value of raw material	[US\$/kg]	0.15
Annual value of raw material	[US\$/year]	150000

Max annual revenue	[US\$/year]	980979
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$$\text{Max annual revenue} = \left(\frac{\text{Annual value}}{\text{of product}} \right) - \left(\frac{\text{Annual value of}}{\text{raw material}} \right)$$

Which means

Max total annual capital allowed to spend	[US\$/year]	980979 (= Max annual revenue)
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If all capital could spend over 5 years,

Total capital allowed to spend in 5 years	[US\$]	4904894 (= 980979 * 5)
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The ratio of (Total capital allowed to spend in 5 years) / (Plant cost installed) of 2.42 is calculated based on the ratio factors given in Table 4.2 in Jebson & Fincham (1994).

If (Total capital allowed to spend in 5 years) = 2.42 x (Plant cost installed)

Then, Max plant cost installed allowed	[US\$]	2026816 (with no other operating costs)
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The sum comes from the ratio factors for:
 Purchased equipment-delivered = 1.00
 Purchased equipment installation = 0.47
 Instrumentation and controls (installed) = 0.18
 Piping (installed) = 0.66
 Electrical (installed) = 0.11

Estimation of the installation cost of cheese vat:

Amount of feed to be processed per day	[kg]	5000 (= Feed)
Density of milk	[kg/m3]	1030
Volume of milk to be processed per day	[m3]	4.85
Number of vat to be used		2
Volume of each vat	[m3]	2.43
Allow 20 % overhead space in each vat,		
Volume of each vat with overhead space	[m3]	2.91
Select diameter of vat	[m]	1.5
Thus, length of vat	[m]	1.6
Purchased cost of a vat	[NZ\$]	8000
Total purchased cost of 2 vats	[NZ\$]	16000
	[US\$]	10240 converted at an exchange rate of 0.64

Step: when selecting key process, check cost of the key process compared with the max capital expenditure.

Key process = cheese reactor & precipitator

Cost of cheese reactor & precipitator = US\$ 0.01 million

Max capital expenditure allowed = US\$ 2.02 million

Here, since the cost of key process (cheese reactor & precipitator) is less than max capital expenditure allowed, cottage cheese production is considered economically viable.

Case Study Two: Small scale milk processing (packed cottage cheese)**Economic analysis of the cottage cheese production in regard to the depleted cream that is not wet-blended:**

Out of 19 kg/h of depleted fat, 12 kg/h is wet-blended into the filtered curd.

Therefore, flow rate of cream left	[kg/hr]	7
Working hours per day	[hr/day]	8
Thus, flow rate of cream	[kg/day]	56

If the product is cream powder,

Working days / year	[day]	200
Value of product	[US\$/kg]	3
Total value of product	[US\$/year]	33600

$$\text{Total value of product} = \left(\frac{\text{cream powder}}{\text{production rate}} \right) \times \left(\frac{\text{Working days}}{\text{per year}} \right) \times \left(\text{Value of product} \right)$$

The raw material is cream,

Value of raw material	[US\$/kg]	2.5
Annual value of raw material	[US\$/year]	28000

$$\text{Max annual revenue} = \left(\frac{\text{Annual value}}{\text{of product}} \right) - \left(\frac{\text{Annual value of}}{\text{raw material}} \right)$$

Max annual revenue	[US\$/year]	5600
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Which means

Max total annual capital allowed to spend [US\$/year] 5600 (= Max annual revenue)

If all capital could spend over 5 years,

Total capital allowed to spend in 5 years [US\$] 28000 (= 5600 * 5)

If (Total capital allowed to spend in 5 years) = 2.42 x (Plant cost installed)

Then, Max plant cost installed allowed [US\$] 11570 (with no other operating costs)

Estimation of the installation cost of freeze drier:

Amount of cream to be processed	[kg/day]	56
Density of cream	[kg/m ³]	940
Volume of cream to be processed	[m ³ /day]	0.06

The loading of freeze drier takes place in the morning, and it is unloaded 8 hours later.

Loading into freeze drier each time	[m ³]	0.48
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Assume cream occupies 10% of freeze drier volume:

So, freeze drier volume [m³/s] 4.77

Purchased cost of freeze drier [NZ\$] 104464

[US\$] 66857 converted at an exchange rate of 0.64

$$\log \left(\frac{\text{Cost of}}{\text{freeze drier}} \right) = 4.90 - 0.401 \times \log \left(\frac{\text{internal}}{\text{volume}} \right) + 0.850 \times \left(\log \left(\frac{\text{internal}}{\text{volume}} \right) \right)^2$$

Step: when selecting key process, check cost of the key process compared with the max capital expenditure.

Key process = freeze drier

Cost of freeze drier = US\$ 66857

Max capital expenditure allowed = US\$ 11570

Here, since the cost of key process (freeze drier) is more than max capital expenditure allowed, cream powder production is economically rejected.

Appendix B – Case Study Three

Medium scale milk processing: Packed Casein Powder

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder*****A comparison of composition of product to raw milk feed in order to determine required component enrichment / depletion***

The following calculations show how the mass balance is calculated for Step 4 of the methodology

Assume that 1 day = 20 production hours.

Feed and product composition are taken from Bylund (1995).

1% is lost as fines in separation

Assumed casein yield = 99 %

	Whole milk feed		Desired product		Depletion and/or enrichment (Product - Feed)	
Mass flow [kg/d]		100000		30282		-969718
Mass flow [kg/hr]		50000		1514		-48486
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	3.9	1950	1.4	21.2	4.0	-1929
Casein	2.6	1300	85.0	1287.0	0.0	-13
Whey Protein	0.65	325	0.5	7.6	0.7	-317
Lactose	4.6	2300	0.1	1.5	4.7	-2298
Minerals & miscellaneous	0.95	475	1.5	22.7	0.9	-452
Water	87.3	43650	11.5	174.1	89.7	-43476
Acid	0.0	0	0.0	< 0.001	0.0	0
Total Solids, TS	12.7	6350	88.5	1340	10.3	-5010

Large negative value
for fat means that there
are excessive amounts
of fat in the feed stream.
An upstream process
must be used
to generate a low-fat
feed stream

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the % yield of casein
- 4) Calculate the flowrate of casein in the product where it is = (flowrate of casein in feed) * (% yield of casein)
- 5) List the required composition of product
- 6) Calculate the total flowrate of product stream where it is = (flowrate of casein in product) / (% of casein in product)
- 7) Calculate the flowrate of other total solids and water in the product stream
- 8) Determine the difference in flowrate of each component between the product and feed i.e. (Product - Feed)
- 9) For each component, a negative value of (Product - Feed) means that that component need depletion while a positive value means enrichment
- 10) Determine the composition of each component in (Product - Feed)

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd precipitation and cooking**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - key process (precipitation) and cooking

Assume that 1 day = 20 production hours.

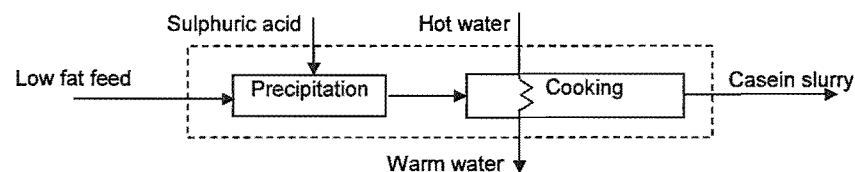
Assume a fat depleted whole milk feed stream

Assumed fat depletion 98.5 %

Slurry heated and cooked then cooled via indirect heating

Sulphuric acid concentration = 10 %

Sulphuric acid dosing 20.0 kg/hr



	Low fat feed		Sulphuric acid		Casein slurry	
Mass flow [kg/d]		961585		400		961985
Mass flow [kg/hr]		48079		20		48099
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.06	29	0.0	0	0.06	29
Casein	2.7	1300	0.0	0	2.7	1300
Whey protein	0.7	325	0.0	0	0.7	325
Lactose	4.8	2300	0.0	0	4.8	2300
Minerals & Miscellaneous	1.0	475	0.0	0	1.0	475
Water	90.8	43650	90.0	18	90.8	43668
Acid	0.0	0	10.0	2	0.004	2
Total Solids, TS	9.2	4429	10.0	2	9.2	4431

Calculation steps

- 1) List the composition of low fat feed and acid streams - low fat stream based on whole milk with 98% fat depletion
- 2) Determine the flowrate of each component in the low fat feed and acid streams
- 3) Calculate component mass flows in slurry as sum of low fat feed and acid streams
- 4) Calculate component concentrations in slurry from mass flows

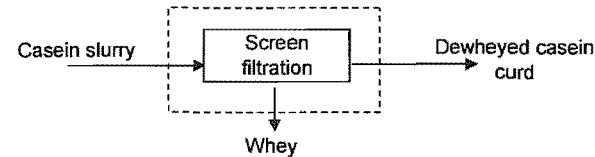
APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over filtration of casein slurry**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - separation of casein curd from whey

Assume that 1 day = 20 production hours.

Feed is casein slurry from precipitation and cooking

Separated curd water content =	80 %
Fat loss in whey =	25 %
Casein loss in whey =	0.8 %
Whey protein loss in whey =	92 %
Lactose loss in whey =	98 %
Minerals loss in whey =	20 %
Acid loss in whey	100 %



	Casein slurry		Whey		Dewheyed casein curd		Desired product (Bylund, 1995)
Mass flow [kg/d]	961985		785631		176354		
Mass flow [kg/hr]	48099		39282		8818		
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w
Fat	0.06	29	0.02	7	0.2	22	1.4
Casein	2.7	1300	0.03	10	14.6	1290	85.0
Whey protein	0.7	325	0.8	299	0.3	26	0.5
Lactose	4.8	2300	5.7	2254	0.5	46	0.1
Minerals & Miscellaneous	1.0	475	0.2	95	4.3	380	1.5
Water	90.8	43668	93.2	36614	80.0	7054	11.5
Acid	0.004	2	0.005	2	0.0	0	< 0.001
Total Solids, TS	9.2	4431	6.8	2668	20.0	1764	88.5

Calculation steps

- 1) List the composition of casein slurry
- 2) Determine the flowrate of each component in the casein slurry stream
- 3) Calculate component mass flows in dewheyed curd from assumed yield values for all except water
- 4) Calculate the total mass flow rate of dewheyed curd using water as a tie-stream

$$= (\text{sum all non-water component flows in dewheyed curd stream}) / (1 - \% \text{ water in dewheyed curd} / 100)$$
- 5) Calculate component concentrations in dewheyed curd stream from mass flows
- 6) Calculate component mass flows in whey stream by difference
- 7) Calculate component concentrations in whey stream from mass flows

Insufficient lactose and minerals
depletion to achieve desired product
composition when dried

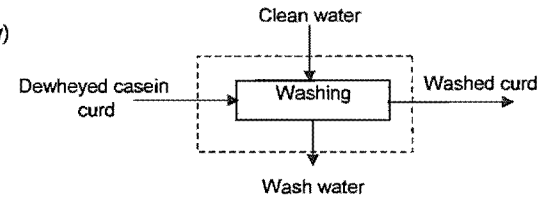
APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd washing**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - curd washing

Assume that 1 day = 20 production hours.

Feed is separated curd

Curd washing rate	200 %	(clean water flow as a % of curd flow)
Washed curd water content =	80 %	
Fat losses during washing =	10 %	
Casein losses during washing =	0.2 %	
Whey protein losses during washing =	70 %	
Lactose losses during washing =	95 %	
Minerals losses during washing =	95 %	
Acid losses during washing =	100 %	



	Dewheyed casein curd		Clean water		Wash water		Washed curd	
Mass flow [kg/d]	176354		352708		395488		133574	
Mass flow [kg/hr]	8818		17635		19774		6679	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.2	22	0.0	0	0.0	2	0.3	20
Casein	14.6	1290	0.0	0	0.0	3	19.3	1287
Whey protein	0.3	26	0.0	0	0.1	18	0.1	8
Lactose	0.5	46	0.0	0	0.2	44	0.0	2
Minerals & Miscellaneous	4.3	380	0.0	0	1.8	361	0.3	19
Water	80.0	7054	100.0	17635	97.8	19347	80.0	5343
Acid	0.00	0	0.0	0	0.0	0	0.0	0
Total Solids, TS	20.0	1764	0.0	0	2.2	428	20.0	1336

Calculation steps

- 1) List the composition of separated curd and clean water streams
- 2) Determine the flowrate of each component in the separated curd and clean water streams
- 3) Calculate mass flow rate of clean water
- 4) Calculate component mass flows in washed curd stream using washing efficiencies
- 5) Calculate the total mass flow rate of washed curd using water as a tie-stream

$$= (\text{sum all non-water component flows in washed curd stream}) / (1 - \% \text{ water in washed curd} / 100)$$
- 6) Calculate component concentrations in the washed curd stream from mass flows
- 7) Calculate component mass flows in wash water stream by difference
- 8) Calculate component concentrations in wash water stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over fluidised curd drier**

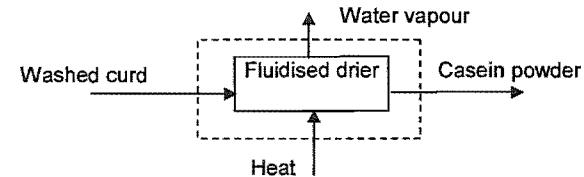
The following calculations show how the mass balance is calculated for Step 8 of the methodology - drying of washed curd

Assume that 1 day = 20 production hours.

Feed is washed curd

Assume only water removed by drying

Dried casein water content = 11.5 %



	Washed curd		Water vapour		Dried casein		Desired product (Bylund, 1995)
Mass flow [kg/d]	133574		103387		30186		
Mass flow [kg/hr]	6679		5169		1509		
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w
Fat	0.3	20	0.0	0	1.3	20	1.4
Casein	19.3	1287	0.0	0	85.3	1287	85.0
Whey protein	0.1	8	0.0	0	0.5	8	0.5
Lactose	0.03	2	0.0	0	0.1	2	0.1
Minerals & Miscellaneous	0.3	19	0.0	0	1.3	19	1.5
Water	80.0	5343	100.0	5169	11.5	174	11.5
Acid	0.0	0	0.0	0	0.0	0	< 0.001
Total Solids, TS	20.0	1336	0.0	0	88.4	1336	88.5

Calculation steps

- 1) List the composition of washed curd stream
- 2) Determine the flowrate of each component in the washed curd stream
- 3) Set component mass flows in water vapour equal to zero for all except water
- 4) Set component concentrations in water vapour equal to zero for all except water
- 5) Calculate component mass flows in dried casein stream by difference for all except water
- 6) Calculate the total mass flow rate of dried casein using moisture as a tie-stream

$$= (\text{sum all non-water component flows in dried casein stream}) / (1 - \% \text{ water in dried casein} / 100)$$
- 7) Calculate mass flow of water vapour by difference

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over centrifugal separator used to remove fat from feed stream prior to casein production**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - centrifugal separation of whole milk feed

Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

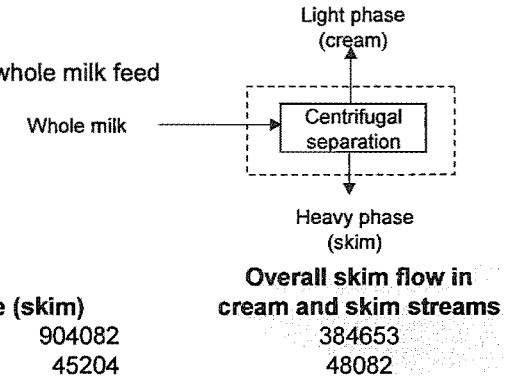
Assume that 1 day = 20 production hours.

Feed composition based on Bylund (1995).

Assumed skim fat concentration = 0.07 %

Assumed cream fat concentration = 40 % (Bylund, 1995)

Assume cream is a mixed stream of fat and skim



	Whole milk feed		Light phase (cream)		Heavy phase (skim)		
Mass flow [kg/d]		1000000		95918		904082	
Mass flow [kg/hr]		50000		4796		45204	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	
Fat	3.9	1950	40.0	1918	0.07	32	
Casein	2.6	1300	1.6	78	2.7	1222	
Whey Protein	0.65	325	0.4	19	0.7	306	
Lactose	4.6	2300	2.9	138	4.8	2162	
Minerals & miscellaneous	0.95	475	0.6	28	1.0	447	
Water	87.3	43650	54.5	2614	90.8	41036	
Acid	0.0	0	0.0	0	0.0	0	
Total Solids, TS	12.7	6350	45.5	2182	9.2	4168	

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the % fat in cream
- 4) Specify the % fat in skim milk
- 5) Calculate the heavy phase flow rate, using fat as the tie-stream = $\text{feed flowrate} \times (\% \text{ feed fat} - \% \text{ cream fat}) / (\% \text{ skim fat} - \% \text{ cream fat})$
- 6) Calculate the total flowrate of skim milk in light and heavy phases
- 7) Calculate the concentrations of other components in heavy phase using feed compositions and total skim flow rate
- 8) Determine the component flows in light phase by difference from feed and heavy streams
- 9) Calculate component concentrations in light phase using component flows and total light phase flow rate

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over microfiltration plant used to remove lactose, minerals and whey protein from feed stream prior to casein production**

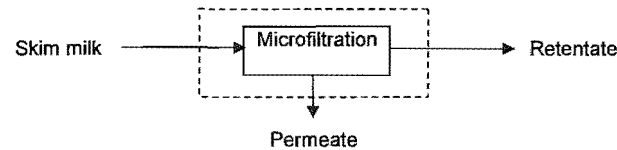
The following calculations show how the mass balance is calculated for Step 9 of the methodology - skim milk microfiltration

Step 8 calculations repeated using microfiltration to deplete lactose, minerals and whey protein prior to curd washing downstream of key process

Assume that 1 day = 20 production hours.

Feed is separated skim milk

Retentate total solids =	15 %
Fat retention =	100 %
Casein retention =	100 %
Whey protein retention =	50 %
Lactose retention =	20 %
Minerals retention =	20 %



	Skim milk feed		Skim permeate		Skim retentate	
Mass flow [kg/d]	904082		646962		257120	
Mass flow [kg/hr]	45204		32348		12856	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.07	32	0.0	0	0.2	32
Casein	2.7	1222	0.0	0	9.5	1222
Whey Protein	0.7	306	0.5	153	1.2	153
Lactose	4.8	2162	5.3	1730	3.4	432
Minerals & miscellaneous	1.0	447	1.1	357	0.7	89
Water	90.8	41036	93.1	30108	85.0	10928
Acid	0.0	0	0.0	0	0.0	0
Total Solids, TS	9.2	4168	6.9	2240	15.0	1928

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Calculate component mass flows in retentate stream using retention values
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX B: Case study three

Medium scale milk processing : Packed casein powder

Component balance over curd precipitation and cooking

The following calculations show how the mass balance is calculated for Step 9 of the methodology - key process (precipitation) and cooking
Step 8 calculations repeated using centrifugal separator to deplete fat, microfiltration to deplete lactose, minerals and whey protein

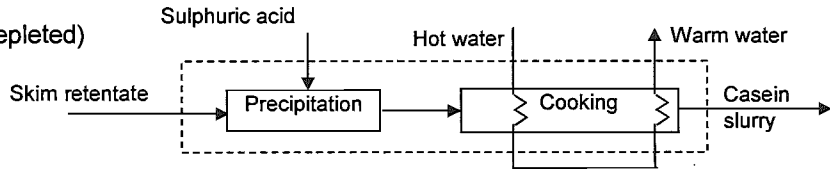
Assume that 1 day = 20 production hours.

Feed stream is skim retentate (fat, minerals, lactose and whey protein depleted)

Slurry heated and cooked then cooled via indirect heating

Sulphuric acid concentration = 10 %

Sulphuric acid dosing 20.0 kg/hr



	Skim retentate		Sulphuric acid		Casein slurry	
Mass flow [kg/d]		257120		400		257520
Mass flow [kg/hr]		12856		20		12876
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.2	32	0.0	0	0.25	32
Casein	9.5	1222	0.0	0	9.5	1222
Whey protein	1.2	153	0.0	0	1.2	153
Lactose	3.4	432	0.0	0	3.4	432
Minerals & Miscellaneous	0.7	89	0.0	0	0.7	89
Water	85.0	10928	90.0	18	85.0	10946
Acid	0.0	0	10.0	2	0.02	2
Total Solids, TS	15.0	1928	10.0	2	15.0	1930

Calculation steps

- 1) List the composition of skim retentate and acid streams
- 2) Determine the flowrate of each component in the skim retentate and acid streams
- 3) Calculate component mass flows in slurry as sum of low fat feed and acid streams
- 4) Calculate component concentrations in slurry from mass flows

APPENDIX B: Case study three

Medium scale milk processing : Packed casein powder

Component balance over filtration of casein slurry

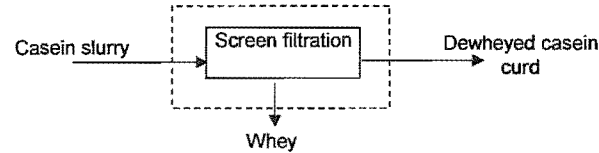
The following calculations show how the mass balance is calculated for Step 9 of the methodology - separation of casein curd from whey

Step 8 calculations repeated using centrifugal separator to deplete fat, microfiltration to deplete lactose, minerals and whey protein

Assume that 1 day = 20 production hours.

Feed is casein slurry from precipitation and cooking. Casein curd precipitated from skim retentate

Separated curd water content =	80 %
Fat loss in whey =	25 %
Casein loss in whey =	0.8 %
Whey protein loss in whey =	92 %
Lactose loss in whey =	98 %
Minerals loss in whey	20 %
Acid loss in whey	100 %



	Casein slurry		Whey		Dewheyed casein curd	
Mass flow [kg/d]	257520		124673		132848	
Mass flow [kg/hr]	12876		6234		6642	
	[% w/w]		[% w/w]		[% w/w]	
	[kg/hr]		[kg/hr]		[kg/hr]	
Fat	0.2	32	0.1	8	0.4	24
Casein	9.5	1222	0.16	10	18.3	1212
Whey protein	1.2	153	2.3	141	0.2	12
Lactose	3.4	432	6.8	424	0.1	9
Minerals & Miscellaneous	0.7	89	0.3	18	1.1	71
Water	85.0	10946	90.3	5632	80.0	5314
Acid	0.0	2	0.03	2	0.0	0
Total Solids, TS	15.0	1930	9.7	602	20.0	1328

Calculation steps

- 1) List the composition of casein slurry
- 2) Determine the flowrate of each component in the casein slurry stream
- 3) Calculate component mass flows in separated curd from assumed yield values for all except water
- 4) Calculate the total mass flow rate of separated curd using water as a tie-stream

$$= (\text{sum all non-water component flows in separated curd stream}) / (1 - \% \text{ water in separated curd} / 100)$$
- 5) Calculate component concentrations in separated curd stream from mass flows
- 6) Calculate component mass flows in whey stream by difference
- 7) Calculate component concentrations in whey stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd washing**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - curd washing

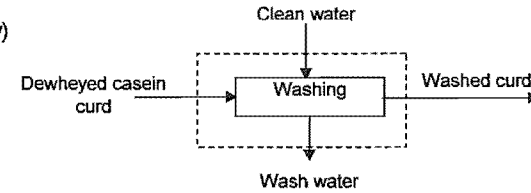
Step 8 calculations repeated using centrifugal separator to deplete fat, microfiltration to deplete lactose, minerals and whey protein

Assume that 1 day = 20 production hours.

Feed is separated curd. Casein curd precipitated from skim retentate

Curd washing rate	160 %	(clean water flow as a % of curd flow)
Washed curd water content =	80 %	
Fat losses during washing =	8 %	
Casein losses during washing =	0 %	
Whey protein losses during washing =	56 %	
Lactose losses during washing =	76 %	
Minerals losses during washing =	76 %	
Acid losses during washing =	80 %	

Washing efficiency assumed to be proportional to washing rate



	Dewheyed casein curd		Clean water		Wash water		Washed curd	
Mass flow [kg/d]	132848		212556		219722		125682	
Mass flow [kg/hr]	6642		10628		10986		6284	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.4	24	0.0	0	0.0	2	0.3	22
Casein	18.3	1212	0.0	0	0.0	2	19.3	1210
Whey protein	0.2	12	0.0	0	0.1	7	0.1	5
Lactose	0.1	9	0.0	0	0.1	7	0.0	2
Minerals & Miscellaneous	1.1	71	0.0	0	0.5	54	0.3	17
Water	80.0	5314	100.0	10628	99.3	10914	80.0	5027
Acid	0.00	0	0.0	0	0.0	0	0.0	0
Total Solids, TS	20.0	1328	0.0	0	0.7	72	20.0	1257

Calculation steps

- 1) List the composition of separated curd and clean water streams
- 2) Determine the flowrate of each component in the separated curd and clean water streams
- 3) Calculate mass flow rate of clean water
- 4) Calculate component mass flows in washed curd stream using washing efficiencies
- 5) Calculate the total mass flow rate of washed curd using water as a tie-stream

$$= (\text{sum all non-water component flows in washed curd stream}) / (1 - \% \text{ water in washed curd} / 100)$$
- 6) Calculate component concentrations in the washed curd stream from mass flows
- 7) Calculate component mass flows in wash water stream by difference
- 8) Calculate component concentrations in wash water stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd drying to produce casein powder**

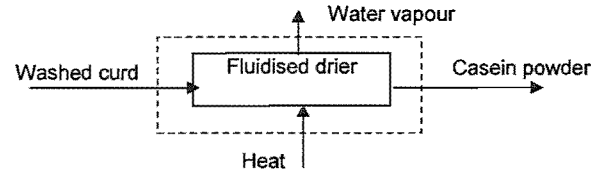
The following calculations show how the mass balance is calculated for Step 9 of the methodology - drying curd to produce casein product
Step 8 calculations repeated using centrifugal separator to deplete fat, microfiltration to deplete lactose, minerals and whey protein

Assume that 1 day = 20 production hours.

Feed is washed curd and recovered casein fines from clarifier (B-12).

Assume only water removed by drying

Dried casein water content = 11.5 %



	Washed curd		Water vapour		Dried casein	
Mass flow [kg/d]	125682		97279		28403	
Mass flow [kg/hr]	6284		4864		1420	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.3	22	0.0	0	1.5	22
Casein	19.3	1210	0.0	0	85.2	1210
Whey protein	0.1	5	0.0	0	0.4	5
Lactose	0.03	2	0.0	0	0.1	2
Minerals & Miscellaneous	0.3	17	0.0	0	1.2	17
Water	80.0	5027	100.0	4864	11.5	163
Acid	0.0	0	0.0	0	0.0	0
Total Solids, TS	20.0	1257	0.0	0	88.5	1257

Microfiltration of skim allows desired product composition to be achieved using 40% less wash water

Desired product (Bylund, 1995)

% w/w	
1.4	
85.0	
0.5	
0.1	
1.5	
11.5	
< 0.001	
88.5	

Calculation steps

- 1) List the composition of washed curd stream feed drier
- 2) Determine the flowrate of each component in the drier feed stream
- 3) Set component mass flows in water vapour equal to zero for all except water
- 4) Set component concentrations in water vapour equal to zero for all except water
- 5) Calculate component mass flows in dried casein stream by difference for all except water
- 6) Calculate the total mass flow rate of dried casein using water as a tie-stream

$$= (\text{sum all non-water component flows in dried casein stream}) / (1 - \% \text{ water in dried casein} / 100)$$
- 7) Calculate mass flow of water vapour by difference

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Heat balance over curd cooking to determine hot water requirements**

The following calculations show how the energy balance is calculated for Step 9 of the methodology - utilities requirement

Step 8 calculations repeated using centrifugal separator to deplete fat, microfiltration to deplete lactose, minerals and whey protein

Assume that 1 day = 20 production hours.

Feed stream is skim retentate (fat, minerals, lactose and whey protein depleted)

Raw curd slurry heated via indirect heating with counter-current heat exchanger

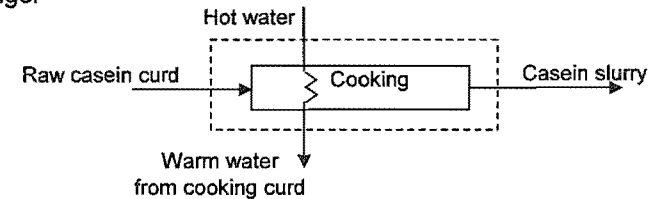
Assumed temperature approach for HX'er = 5 °C

Heating casein to cook temp**Process side**

Mass flow [kg/d]	257520
Mass flow [kg/hr]	12876
Initial temperature [°C]	12
Final temperature [°C]	60
Specific heat [kJ/kg/°C]	4.5
Required heat duty [kW]	773

Utility side - separate streams

Required heat duty [kW]	773
Specific heat [kJ/kg/°C]	4.2
Initial temperature [°C]	85
Final temperature [°C]	17
Required mass flow [kg/hr]	9738
Required mass flow [kg/d]	194763

**Calculation steps**

- 1) Calculate required duty to heat curd to cook temperature
- 2) Calculate necessary mass flow rate of hot water to deliver required heat duty

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd precipitation and cooking**

The following calculations show how the mass balance is calculated for Step 13 of the methodology - key process (precipitation) and cooking

Step 10 calculations repeated with side stream integration

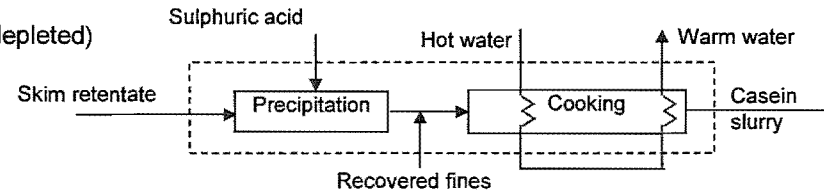
Assume that 1 day = 20 production hours.

Feed stream is skim retentate (fat, minerals, lactose and whey protein depleted)

Slurry heated and cooked then cooled via indirect heating

Sulphuric acid concentration = 10 %

Sulphuric acid dosing 20.0 kg/hr



	Skim retentate		Sulphuric acid		Clarifier fines		Casein slurry	
Mass flow [kg/d]	257120		400		634		258154	
Mass flow [kg/hr]	12856		20		32		12908	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.2	32	0.0	0	0.04	0.01	0.25	32
Casein	9.5	1222	0.0	0	37.6	12	9.6	1234
Whey protein	1.2	153	0.0	0	0.5	0.2	1.2	153
Lactose	3.4	432	0.0	0	1.6	0.5	3.4	433
Minerals & Miscellaneous	0.7	89	0.0	0	0.3	0.1	0.7	89
Water	85.0	10928	90.0	18	60.0	19	84.9	10965
Acid	0.0	0	10.0	2	0.01	0.002	0.02	2
Total Solids, TS	15.0	1928	10.0	2	40.0	13	15.1	1943

Estimated clarifier
fines composition

Calculation steps

- 1) List the composition of skim retentate and acid streams
- 2) Determine the flowrate of each component in the skim retentate and acid streams
- 3) Estimate likely component concentrations and overall mass flow in clarifier fines
- 4) Calculate component mass flows in clarifier fines stream
- 5) Calculate component mass flows in slurry as sum of skim retentate, fines and acid streams
- 6) Calculate component concentrations in slurry from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over filtration of casein slurry**

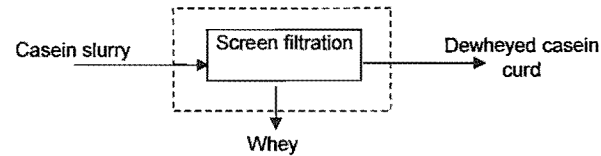
The following calculations show how the mass balance is calculated for Step 13 of the methodology - separation of casein curd from whey

Step 10 calculations repeated with side stream integration

Assume that 1 day = 20 production hours.

Feed is casein slurry from precipitation and cooking. Casein curd precipitated from skim retentate

Separated curd water content =	80 %
Fat loss in whey =	25 %
Casein loss in whey =	0.8 %
Whey protein loss in whey =	92 %
Lactose loss in whey =	98 %
Minerals loss in whey	20 %
Acid loss in whey	100 %



	Casein slurry		Whey		Dewheyed casein curd	
Mass flow [kg/d]	258154		124113		134041	
Mass flow [kg/hr]	12908		6206		6702	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.2	32	0.1	8	0.4	24
Casein	9.6	1234	0.16	10	18.3	1224
Whey protein	1.2	153	2.3	141	0.2	12
Lactose	3.4	433	6.8	424	0.1	9
Minerals & Miscellaneous	0.7	89	0.3	18	1.1	72
Water	84.9	10965	90.3	5603	80.0	5362
Acid	0.0	2	0.03	2	0.0	0
Total Solids, TS	15.1	1943	9.7	603	20.0	1340

Calculation steps

- 1) List the composition of casein slurry
- 2) Determine the flowrate of each component in the casein slurry stream
- 3) Calculate component mass flows in separated curd from assumed yield values for all except water
- 4) Calculate the total mass flow rate of separated curd using water as a tie-stream

$$= (\text{sum all non-water component flows in separated curd stream}) / (1 - \% \text{ water in separated curd} / 100)$$
- 5) Calculate component concentrations in separated curd stream from mass flows
- 6) Calculate component mass flows in whey stream by difference
- 7) Calculate component concentrations in whey stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd washing**

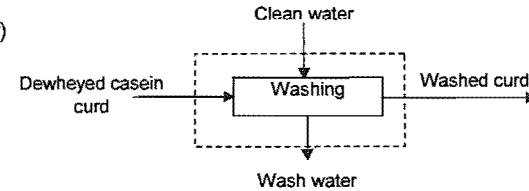
The following calculations show how the mass balance is calculated for Step 13 of the methodology - curd washing

Step 10 calculations repeated with side stream integration

Assume that 1 day = 20 production hours.

Feed is separated curd. Casein curd precipitated from skim retentate

Curd washing rate	160 %	(clean water flow as a % of curd flow)
Washed curd water content =	80 %	
Fat losses during washing =	8 %	
Casein losses during washing =	0 %	
Whey protein losses during washing =	56 %	← Washing efficiency assumed to be proportional to washing rate
Lactose losses during washing =	76 %	
Minerals losses during washing =	76 %	
Acid losses during washing =	80 %	



	Dewheyed casein curd		Clean water		Wash water		Washed curd	
Mass flow [kg/d]	134041		214465		221640		126867	
Mass flow [kg/hr]	6702		10723		11082		6343	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.4	24	0.0	0	0.0	2	0.3	22
Casein	18.3	1224	0.0	0	0.0	2	19.3	1222
Whey protein	0.2	12	0.0	0	0.1	7	0.1	5
Lactose	0.1	9	0.0	0	0.1	7	0.0	2
Minerals & Miscellaneous	1.1	72	0.004	0.4	0.5	55	0.3	17
Water	80.0	5362	99.996	10723	99.3	11010	80.0	5075
Acid	0.00	0	0.0001	0.01	0.0	0	0.0	0
Total Solids, TS	20.0	1340	0.0	0	0.7	72	20.0	1269

Calculation steps

- 1) List the composition of separated curd and clean water streams
- 2) Determine the flowrate of each component in the separated curd and clean water streams
- 3) Calculate mass flow rate of clean water
- 4) Calculate component mass flows in washed curd stream using washing efficiencies
- 5) Calculate the total mass flow rate of washed curd using water as a tie-stream
= (sum all non-water component flows in washed curd stream)/(1-% water in washed curd/100)
- 6) Calculate component concentrations in the washed curd stream from mass flows
- 7) Calculate component mass flows in wash water stream by difference
- 8) Calculate component concentrations in wash water stream from mass flows

Estimated clean water composition
from RO polisher permeate

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over curd drying to produce casein powder**

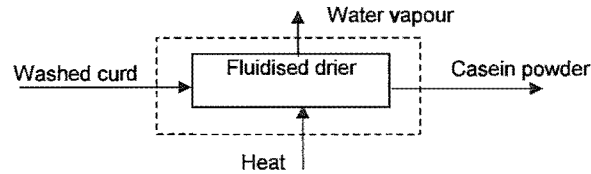
The following calculations show how the mass balance is calculated for Step 13 of the methodology - drying curd to produce casein product
Step 10 calculations repeated with side stream integration

Assume that 1 day = 20 production hours.

Feed is washed curd and recovered casein fines from clarifier (B-12).

Assume only water removed by drying

Dried casein water content = 11.5 %



	Washed curd		Water vapour		Dried casein	
Mass flow [kg/d]	126867		98196		28670	
Mass flow [kg/hr]	6343		4910		1434	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.3	22	0.0	0	1.4	22
Casein	19.3	1222	0.0	0	85.3	1222
Whey protein	0.1	5	0.0	0	0.4	5
Lactose	0.03	2	0.0	0	0.1	2
Minerals & Miscellaneous	0.3	17	0.0	0	1.2	17
Water	80.0	5075	100.0	4910	11.5	165
Acid	0.0	0	0.0	0	0.0	0
Total Solids, TS	20.0	1269	0.0	0	88.4	1269

Microfiltration of skim allows desired product composition to be achieved using 40% less wash water

Desired product (Bylund, 1995)

	% w/w
	1.4
	85.0
	0.5
	0.1
	1.5
	11.5
	< 0.001
	88.5

Calculation steps

- 1) List the composition of washed curd stream feed drier
- 2) Determine the flowrate of each component in the drier feed stream
- 3) Set component mass flows in water vapour equal to zero for all except water
- 4) Set component concentrations in water vapour equal to zero for all except water
- 5) Calculate component mass flows in dried casein stream by difference for all except water
- 6) Calculate the total mass flow rate of dried casein using water as a tie-stream
= (sum all non-water component flows in dried casein stream)/(1-% water in dried casein/100)
- 7) Calculate mass flow of water vapour by difference

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over clarifier processing combined whey and wash water streams**

The following calculations show how the mass balance is calculated for Step 13 of the methodology - process integration

Step 10 calculations repeated with side stream integration

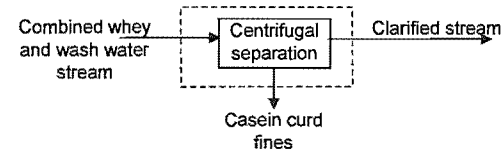
Whey and wash water must be clarified to remove casein fines before being processed by RO plant

Assume that 1 day = 20 production hours.

Feed is wash water streams

Water content of clarifier fines = 60 %

Clarifier efficiency 100 %



	Whey and wash water		Clarifier fines		Clarified whey & wash water	
Mass flow [kg/d]	345753		634		345119	
Mass flow [kg/hr]	17288		32		17256	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.06	9.8	0.04	0.01	0.06	9.8
Casein	0.07	11.9	37.6	11.9	0.0	0.0
Whey protein	0.9	147.6	0.5	0.2	0.9	147.4
Lactose	2.5	430.9	1.6	0.5	2.5	430.4
Minerals & Miscellaneous	0.4	72.6	0.26	0.08	0.4	72.5
Water	96.1	16612.8	60.0	19.0	96.2	16593.8
Acid	0.01	2.0	0.01	0.002	0.01	2.0
Total Solids, TS	3.9	675	40.0	13	3.8	662

Calculation steps

- 1) List the composition of feed stream
- 2) Determine the flowrate of each component in feed stream
- 3) Estimate total mass flow rate of clarifier fines
- 4) Calculate mass flow of casein in clarified stream by difference
- 5) Calculate overall mass flow of clarified stream by difference
- 6) Calculate component mass flows in clarified stream

$$= \text{component mass flow in feed} \times (\text{overall mass flow of clarified stream} / (\text{overall mass flow of clarified stream} + \text{overall mass flow of clarifier fines stream} - \text{mass flow of casein in clarifier fines}))$$
- 7) Calculate component concentrations in the clarified stream from component and overall mass flows
- 8) Calculate component mass flows in clarifier fines stream by difference
- 9) Calculate component concentrations in the clarifier fines stream from component and overall mass flows
- 10) Manipulate total mass flow of clarifier fines until desired % water is achieved
- 11) Update component concentrations and overall mass flows for curd fines in curd precipitation and cooking (B-8)

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over NF plant processing clarified casein whey and wash water**

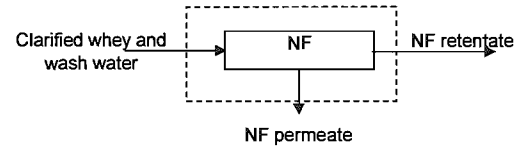
The following calculations show how the mass balance is calculated for Step 13 of the methodology - process integration

Step 10 calculations repeated with side stream integration

Assume that 1 day = 20 production hours.

Feed is clarified wash water and whey stream

Retentate total solids =	10 %
Overall fat retention =	100 %
Overall casein retention =	100 %
Overall whey protein retention =	100 %
Overall lactose retention =	100 %
Overall minerals retention =	50 %
Overall acid retention =	50 %



	Clarified whey & wash water		NF retentate		NF permeate	
Mass flow [kg/d]		345119		124971		220148
Mass flow [kg/hr]		17256		6249		11007
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.1	10	0.2	10	0.0	0
Casein	0.0	0	0.0	0	0.0	0
Whey protein	0.85	147	2.4	147	0.0	0
Lactose	2.5	430	6.9	430	0.0	0
Minerals & Miscellaneous	0.4	73	0.6	36	0.3	36
Water	96.2	16594	90.0	5624	99.7	10970
Acid	0.0	2	0.0	1	0.0	1
Total Solids, TS	3.84	662	10.0	625	0.3	37

Calculation steps

- 1) List the composition of feed streams
- 2) Determine the flowrate of each component in the feed streams
- 3) Calculate component mass flows in retentate stream using retention values, and feed stream component mass flow rates
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder****Component balance over RO polisher plant processing NF permeate**

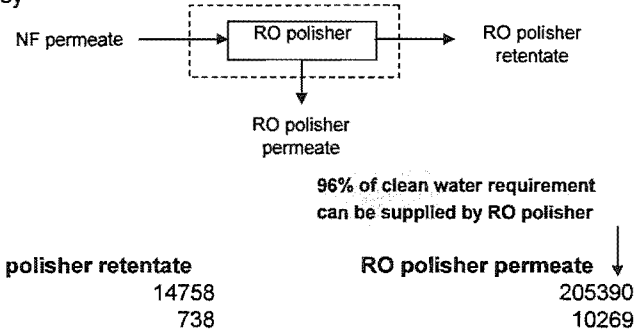
The following calculations show how the mass balance is calculated for Step 13 of the methodology - process integration

Step 10 calculations repeated with side stream integration

Feed is permeate from NF plant processing clarified wash water and whey

Assume that 1 day = 20 production hours.

Retentate total solids =	5 %
Overall fat retention =	100 %
Overall casein retention =	100 %
Overall whey protein retention =	100 %
Overall lactose retention =	100 %
Overall minerals retention =	99 %
Overall acid retention =	99 %



	NF permeate		RO polisher retentate		RO polisher permeate	
Mass flow [kg/d]		220148		14758		205390
Mass flow [kg/hr]		11007		738		10269
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.0	0	0.0	0	0.0	0
Casein	0.0	0	0.0	0	0.0	0
Whey protein	0.0	0	0.0	0	0.0	0
Lactose	0.0	0	0.0	0	0.0	0
Minerals & Miscellaneous	0.3	36	4.9	36	0.004	0.4
Water	99.7	10970	95.0	701	99.996	10269
Acid	0.01	1	0.1	1	0.0001	0.01
Total Solids, TS	0.34	37	5.0	37	0.00	0
			95.8			

Calculation steps

- 1) List the composition of feed streams
- 2) Determine the flowrate of each component in the feed streams
- 3) Calculate component mass flows in retentate stream using retention values, and feed stream component mass flow rates
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder*****Heat balance over curd cooking to determine hot water requirements***

The following calculations show how the energy balance is calculated for Step 13 of the methodology - process integration

Step 10 calculations repeated with side stream integration

Assume that 1 day = 20 production hours.

Feed stream is skim retentate (fat, minerals, lactose and whey protein depleted)

Raw curd slurry heated via indirect heating with counter-current heat exchanger

Assumed temperature approach for HX'er = 5 °C

Heating casein to cook temp

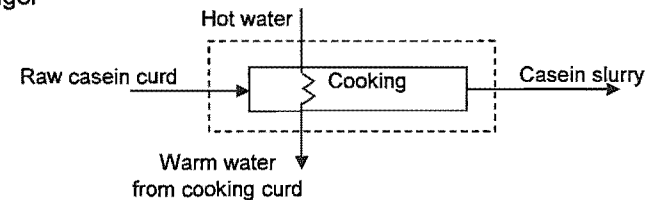
	Process side
Mass flow [kg/d]	258154
Mass flow [kg/hr]	12908
Initial temperature [°C]	12
Final temperature [°C]	60
Specific heat [kJ/kg/°C]	4.5
Required heat duty [kW]	774

Utility side - separate streams

Required heat duty [kW]	774
Specific heat [kJ/kg/°C]	4.2
Initial temperature [°C]	85
Final temperature [°C]	17
Required mass flow [kg/hr]	9762
Required mass flow [kg/d]	195243

Calculation steps

- 1) Calculate required duty to heat curd to cook temperature
- 2) Calculate necessary mass flow rate of hot water to deliver required heat duty



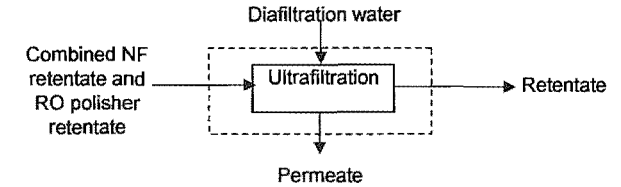
APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder with integrated WPC powder production****Component balance over UF plant processing combined NF and RO polisher retentate streams**

The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing

Assume that 1 day = 20 production hours.

Feed is combined retentate streams from NF & RO polisher plants

Overall diafiltration ratio =	12 %	
Retentate total solids =	24 %	
Overall fat retention =	100 %	
Overall casein retention =	100 %	
Overall whey protein retention =	90 %	← Use of diafiltration reduces retention of lactose and minerals
Overall lactose retention =	3.8 %	
Overall minerals retention =	1.5 %	
Overall acid retention =	0.5 %	



	NF retentate & RO polisher retentate		Diafiltration water		WPC UF permeate		WPC UF retentate	
Mass flow [kg/d]	139729		16767		143189		13307	
Mass flow [kg/hr]	6986		838		7159		665	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.1	10	0.0	0	0.0	0	1.5	10
Casein	0.0	0	0.0	0	0.0	0	0.0	0
Whey Protein	2.1	147	0.0	0	0.2	15	19.9	133
Lactose	6.2	430	0.0	0	5.8	414	2.4	16
Minerals & miscellaneous	1.0	72	0.0	0	1.0	71	0.2	1
Water	90.5	6325	100.0	838	93.0	6657	76.0	506
Acid	0.0	2	0.0	0	0.0	2	0.002	0.01
Total Solids, TS	9.5	662	0.0	0	7.0	502	24.0	160

Calculation steps

- 1) List the composition of feed and diafiltration streams
- 2) Determine the flowrate of each component in the feed and diafiltration streams
- 3) Calculate component mass flows in retentate stream using retention values
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference from feed and diafiltration flows
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX B: Case study three

Medium scale milk processing : Packed casein powder with integrated WPC powder production

Component balance over evaporator processing WPC UF retentate

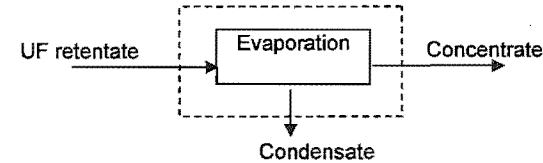
The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing

Assume that 1 day = 20 production hours.

Feed is WPC UF retentate

Assume only water removed by evaporation

Evaporator concentrate total solids 40 %



	WPC UF retentate		Evap condensate		Evap concentrate	
Mass flow [kg/d]	13307		5323		7984	
Mass flow [kg/hr]	665		266		399	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	1.5	10	0.0	0	2.5	10
Casein	0.0	0	0.0	0	0.0	0
Whey protein	19.9	133	0.0	0	33.2	133
Lactose	2.4	16	0.0	0	4.0	16
Minerals & Miscellaneous	0.2	1	0.0	0	0.3	1
Water	76.0	506	100.0	266	60.0	240
Acid	0.002	0.01	0.0	0	0.003	0.01
Total Solids, TS	24.0	160	0.0	0	40.0	160

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Calculate component mass flows in concentrate assuming no solids loss in condensate
- 4) Calculate the total mass flow rate of concentrate using water as a tie-stream

$$= (\text{sum all non-water component flows in concentrate}) / (1 - \% \text{ water in concentrate} / 100)$$
- 5) Calculate component concentrations in concentrate stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder with integrated WPC powder production****Component balance over spray drier processing evaporator concentrate to produce WPC powder**

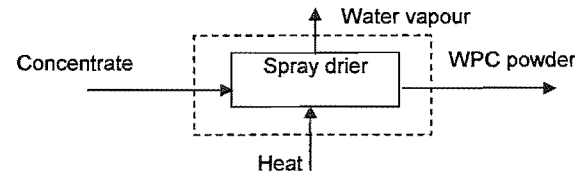
The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing

Assume that 1 day = 20 production hours.

Feed is evaporator concentrate

Assume only water removed by drying

Dried WPC powder water content = 4 %



	Washed curd		Water vapour		Dried WPC		Desired product (Based on Winchester, 1996)
Mass flow [kg/d]		7984		4658		3327	
Mass flow [kg/hr]		399		233		166	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w
Fat	2.5	10	0.0	0	5.9	10	6.0
Casein	0.0	0	0.0	0	0.0	0	0.0
Whey protein	33.2	133	0.0	0	79.7	133	79.5
Lactose	4.0	16	0.0	0	9.7	16	9.7
Minerals & Miscellaneous	0.3	1	0.0	0	0.7	1	0.8
Water	60.0	240	100.0	233	4.0	7	4.0
Acid	0.003	0.01	0.0	0	0.006	0.01	> 0.01
Total Solids, TS	40.0	160	0.0	0	96.0	160	96.0

Calculation steps

- 1) List the composition of feed stream
- 2) Determine the mass flowrate of each component in the feed
- 3) Set component mass flows in water vapour equal to zero for all except water
- 4) Set component concentrations in water vapour equal to zero for all except water
- 5) Calculate component mass flows in WPC powder stream by difference for all except water
- 6) Calculate the total mass flow rate of WPC powder using water as a tie-stream

$$= (\text{sum all non-water component flows in WPC powder stream}) / (1 - \% \text{ water in WPC powder} / 100)$$
- 7) Calculate mass flow of water vapour by difference

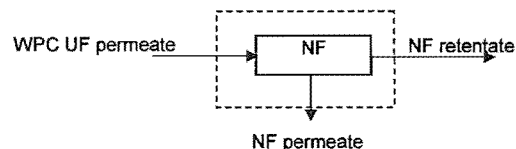
APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder with integrated WPC powder production****Component balance over NF plant processing WPC UF permeate**

The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing

Assume that 1 day = 20 production hours.

Feed is WPC UF permeate

Retentate total solids =	18 %
Overall fat retention =	100 %
Overall casein retention =	100 %
Overall whey protein retention =	100 %
Overall lactose retention =	100 %
Overall minerals retention =	50 %
Overall acid retention =	50 %



	WPC UF permeate		NF retentate		NF permeate	
Mass flow [kg/d]	143189		51725		91464	
Mass flow [kg/hr]	7159		2586		4573	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.0	0	0.0	0	0.0	0
Casein	0.0	0	0.0	0	0.0	0
Whey protein	0.2	15	0.6	15	0.0	0
Lactose	5.8	414	16.0	414	0.0	0
Minerals & Miscellaneous	1.0	71	1.4	36	0.8	36
Water	93.0	6657	82.0	2121	99.2	4537
Acid	0.0	2	0.038	1	0.022	1
Total Solids, TS	7.0	502	18.0	466	0.8	37

Calculation steps

- 1) List the composition of feed streams
- 2) Determine the flowrate of each component in the feed streams
- 3) Calculate component mass flows in retentate stream using retention values, and feed stream component mass flow rates
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

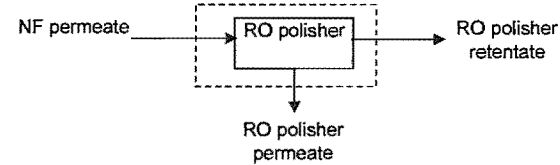
APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder with integrated WPC powder production****Component balance over RO polisher plant processing NF retentate generated from WPC UF permeate**

The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing

Assume that 1 day = 20 production hours.

Feed is permeate from NF plant processing WPC UF permeate

Retentate total solids =	5 %
Overall fat retention =	100 %
Overall casein retention =	100 %
Overall whey protein retention =	100 %
Overall lactose retention =	100 %
Overall minerals retention =	99 %
Overall acid retention =	99 %



	NF permeate		RO polisher retentate		RO polisher permeate	
Mass flow [kg/d]		91464		14468		76996
Mass flow [kg/hr]		4573		723		3850
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	0.0	0	0.0	0	0.0	0
Casein	0.0	0	0.0	0	0.0	0
Whey protein	0.0	0	0.0	0	0.0	0
Lactose	0.0	0	0.0	0	0.0	0
Minerals & Miscellaneous	0.8	36	4.9	35	0.009	0.4
Water	99.2	4537	95.0	687	99.99	3849
Acid	0.0	1	0.1	1	0.0	0
Total Solids, TS	0.80	37	5.0	36	0.01	0

Calculation steps

- 1) List the composition of feed streams
- 2) Determine the flowrate of each component in the feed streams
- 3) Calculate component mass flows in retentate stream using retention values, and feed stream component mass flow rates
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX B: Case study three**Medium scale milk processing : Packed casein powder with integrated WPC powder production*****Heat balance to investigate possible integration between WPC evaporator and WPC NF/RO polisher plants***

The following calculations show how the mass balance is calculated for Step 14 of the methodology - co-product processing
WPC evaporator produces hot condensate. WPC NF and RO polisher plants require heat to operate

Assume that 1 day = 20 production hours.

WPC evaporator condensate temp 50 °C

WPC UF operating temp 10 °C

Assumed operating temp for NF & RO polisher plants 30 °C

Assumed temperature approach for HX'er = 5 °C

	Heating NF feed to operating temp	Heating RO polisher feed to operating temp
	Process side	
Mass flow [kg/d]	143189	91464
Mass flow [kg/hr]	7159	4573
Initial temperature [°C]	10	10
Final temperature [°C]	30	30
Specific heat [kJ/kg/°C]	4.5	4.5
Required heat duty [kW]	179	114
	Utility side	
Required heat duty [kW]	179	114
Specific heat [kJ/kg/°C]	4.2	4.2
Initial temperature [°C]	50	50
Final temperature [°C]	15	15
Required condensate flow [kg/hr]	4383	2800
Required condensate flow [kg/d]	87667	55998
Available condensate flow [kg/hr]	266	
Available condensate flow [kg/d]	5323	

Evaporator condensate can only supply 6% of the hot water requirements for NF and RO polisher plants, so integration is not worthwhile

Calculation steps

- 1) Calculate required heat duty to heat NF and RO polisher feed streams to operating temp
- 2) Calculate required mass flow rate of condensate required to supply net duty, using specified approach temperatures

Appendix C – Case Study Four

Large scale milk processing: Packed Whole Milk Powder

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder*****A comparison of composition of product to raw milk feed in order to determine required component enrichment / depletion***

The following calculations show how the mass balance is calculated for Step 4 of the methodology

Assume that 1 day = 24 production hours.

Feed and product composition are based on Walstra *et al.* (1999).

For initial calculations, it is assumed that all components except casein can be depleted or enriched

Assumed casein yield = 100 %

	Whole milk feed		Desired product		Depletion and/or enrichment (Product - Feed)	
Mass flow [kg/d]	2000000		266667		-1733333	
Mass flow [kg/hr]	83333		11111		-72222	
	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]	[% w/w]	[kg/hr]
Fat	3.9	3250	26.0	2889	0.5	-361
Casein	2.6	2167	19.5	2167	0.0	0
Whey Protein	0.65	544	4.9	544	0.0	0
Lactose	4.6	3833	38.0	4222	-0.5	389
Minerals & miscellaneous	0.95	792	8.1	900	-0.2	108
Water	87.3	72750	3.5	389	100.2	-72361
Total Solids, TS	12.7	10586	96.5	10722	-0.2	136

Large negative value
for moisture means that
moisture removal is an
important part of
of milk powder
production

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the desired component % in product
- 4) Calculate the product flow rate, using casein (assuming no enrichment or depletion) = feed mass flow casein / (% product casein/100)
- 5) Calculate the remaining component mass flows using desired component concentrations in product and overall product flow rate
- 6) Determine the difference in flowrate of each component between the product and feed i.e. (Product - Feed)
- 7) For each component, a negative value of (Product - Feed) means component depletion is required while a positive value means enrichment is necessary
- 8) Determine the composition of each component in (Product - Feed)

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over spray drier producing high moisture powder, for subsequent drying and lactose dry-blending**

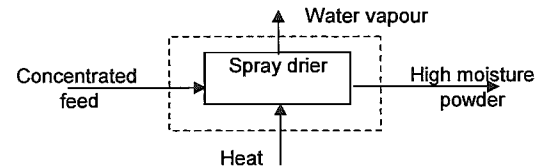
The following calculations show how the mass balance is calculated for Step 8 of the methodology - spray drying

Assume that 1 day = 24 production hours.

Feed is whole milk that has been moisture depleted, with minerals enriched to meet product composition of Walstra *et al.* (1999). Lactose not enriched - same as whole milk feed.

Assumed feed total solids 50 %

Assumed powder moisture = 8 %



	Concentrated feed			Water vapour			High moisture powder	
Mass flow [kg/d]	496000			226435			269565	
Mass flow [kg/hr]	20667			9435			11232	
	[% w/w]	[kg/hr]		[% w/w]	[kg/hr]		[% w/w]	[kg/hr]
Fat	14.0	2889		0.0	0		25.7	2889
Casein	10.5	2167		0.0	0		19.3	2167
Whey Protein	2.6	544		0.0	0		4.8	544
Lactose	18.5	3833		0.0	0		34.1	3833
Minerals & miscellaneous	4.4	900	Same mass	0.0	0		8.0	900
Water	50.0	10333	flow as whole milk feed	100.0	9435		8.0	899
Total Solids, TS	50.0	10333		0.0	0		92.0	10333

Calculation steps

- 1) Set component mass flows in concentrated feed stream to be equal to desired whole milk product values, except for water
- 2) Calculate the total mass flow of concentrated feed using water as a tie-stream

$$= (\text{sum all non-water component mass flows in concentrated feed}) / (1 - \% \text{ water in concentrated feed} / 100)$$
- 3) Set component concentrations in water vapour equal to zero for all except water
- 4) Calculate component mass flows in high moisture powder stream by difference for all except water
- 5) Calculate the total mass flow rate of high moisture powder using water as a tie-stream

$$= (\text{sum all non-water component mass flows in high moisture powder stream}) / (1 - \% \text{ water in high moisture powder} / 100)$$
- 6) Calculate remaining component concentrations in high moisture powder using component mass flows and overall mass flow
- 7) Calculate mass flow of water vapour by difference

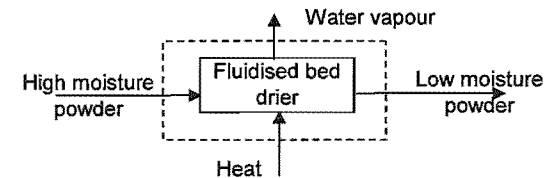
APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over fluidised bed drier producing low moisture powder, for subsequent lactose dry-blending**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - fluidised drying then dry blending
Assume that 1 day = 24 production hours.

Feed is whole milk that has been moisture depleted, with minerals enriched to meet product composition of Walstra *et al.* (1999). Lactose not enriched - same as whole milk feed.

Feed moisture = 8 %

Product moisture = 3.5 %



	High moisture powder			Water vapour			Low moisture powder	
Mass flow [kg/d]	269565			12570			256995	
Mass flow [kg/hr]	11232			524			10708	
	% w/w	[kg/hr]		% w/w	[kg/hr]		% w/w	[kg/hr]
Fat	25.7	2889		0.0	0		27.0	2889
Casein	19.3	2167		0.0	0		20.2	2167
Whey Protein	4.8	544		0.0	0		5.1	544
Lactose	34.1	3833		0.0	0		35.8	3833
Minerals & miscellaneous	8.0	900	Same mass flow as whole milk feed	0.0	0		8.4	900
Water	8.0	899		100.0	524		3.5	375
Total Solids, TS	92.0	10333		0.0	0		96.5	10333

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Set component concentrations in water vapour equal to zero for all except water
- 4) Calculate component mass flows in product stream by difference for all except water
- 5) Calculate the total mass flow rate of low moisture powder using water as a tie-stream

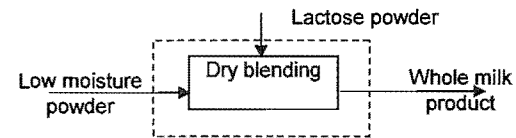
$$= (\text{sum all non-water component mass flows in low moisture powder stream}) / (1 - \% \text{ water in low moisture powder} / 100)$$
- 6) Calculate remaining component concentrations in low moisture powder using component mass flows and overall mass flow
- 7) Calculate mass flow of water vapour by difference

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over dry blending operation adding lactose to produce whole milk powder product**

The following calculations show how the mass balance is calculated for Step 8 of the methodology - dry blending
Assume that 1 day = 24 production hours.

Feed is whole milk that has been moisture depleted, with minerals enriched to meet product composition of Walstra *et al.* (1999). Lactose not enriched - same as whole milk feed.

Final product moisture =	3.5 %
Fat content of lactose powder =	0 %
Casein content of lactose powder =	0 %
Whey protein content of lactose powder =	0 %
Lactose content of lactose powder =	96.5 %
Minerals content of lactose powder =	0 %
Water content of lactose powder =	3.5 %



	Low moisture powder			Lactose powder			Final product			Desired product (Based on Walstra <i>et al.</i> , 1999)	
Mass flow [kg/d]	256995			9672			266667				
Mass flow [kg/hr]	10708			403			11111				
	[% w/w] [kg/hr]			[% w/w] [kg/hr]			[% w/w] [kg/hr]			[% w/w]	
Fat	27.0	2889		0.0	0		26.0	2889		26.0	
Casein	20.2	2167		0.0	0		19.5	2167		19.5	
Whey Protein	5.1	544		0.0	0		4.9	544		4.9	
Lactose	35.8	3833		96.5	389		38.0	4222		38.0	
Minerals & miscellaneous	8.4	900	Same mass flow as whole milk feed	0.0	0		8.1	900		8.1	
Water	3.5	375		3.5	14		3.5	389		3.5	
Total Solids, TS	96.5	10333		96.5	389		96.5	10722		96.5	

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Calculate the required total mass flow of lactose powder using lactose as a tie-stream

$$= (\text{sum all non-lactose component mass flows in lactose powder}) / (1 - \% \text{ lactose in lactose powder} / 100)$$
- 4) Calculate remaining component concentrations in lactose powder using component mass flows and overall mass flow
- 5) Calculate component mass flows in final product by difference
- 6) Calculate component concentrations in final product using component mass flows and overall mass flow

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over centrifugal separator used to remove fat from feed stream prior to RO processing**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - centrifugal separation of whole milk feed

Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

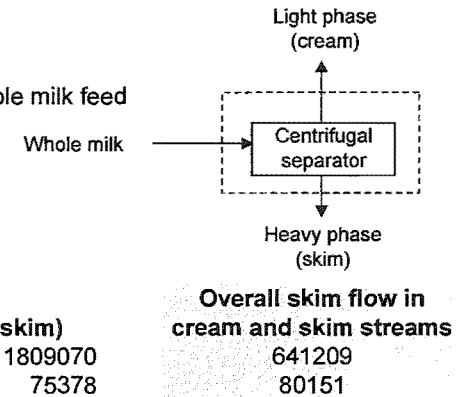
Assume that 1 day = 24 production hours.

Whole milk feed based on Walstra *et al.* (1999).

Assumed skim fat concentration = 0.09 % (hot separation, Bylund, 1995)

Assumed cream fat concentration = 40 % (Bylund, 1995)

Assume cream is a mixed stream of fat and skim



	Whole milk feed		Light phase (cream)		Heavy phase (skim)	
Mass flow [kg/d]	2000000		190930		1809070	
Mass flow [kg/hr]	83333		7955		75378	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	3.9	3250	40.0	3182	0.09	68
Casein	2.6	2167	1.6	129	2.7	2038
Whey Protein	0.7	544	0.4	32	0.7	512
Lactose	4.6	3833	2.9	228	4.8	3605
Minerals & miscellaneous	1.0	792	0.6	47	1.0	745
Water	87.3	72750	54.5	4332	90.8	68418
Total Solids, TS	12.7	10586	45.5	3619	9.2	6967

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify the % fat in cream
- 4) Specify the % fat in skim milk
- 5) Calculate the heavy phase flow rate, using fat as the tie-stream = $\text{feed flowrate} \times (\% \text{ feed fat} - \% \text{ cream fat}) / (\% \text{ skim fat} - \% \text{ cream fat})$
- 6) Calculate the total flowrate of skim milk in light and heavy phases
- 7) Calculate the concentrations of other components in heavy phase using feed compositions and total skim flow rate
- 8) Determine the component flows in light phase by difference from feed and heavy streams
- 9) Calculate component concentrations in light phase using component flows and total light phase flow rate

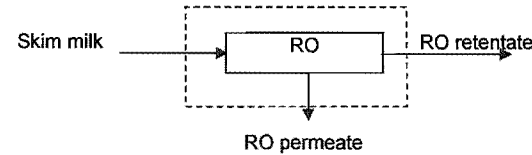
APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over RO plant concentrating skim feed to evaporator**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - skim milk concentration by RO
Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

Feed is skim milk from centrifugal separator

Retentate total solids =	18 %
Fat retention =	100 %
Casein retention =	100 %
Whey protein retention =	100 %
Lactose retention =	99 %
Minerals retention =	80 %



	Skim milk		RO retentate		RO permeate	
Mass flow [kg/d]		1809070		904246		904824
Mass flow [kg/hr]		75378		37677		37701
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.09	68	0.2	68	0.0	0
Casein	2.7	2038	5.4	2038	0.0	0
Whey protein	0.7	512	1.4	512	0.0	0
Lactose	4.8	3605	9.5	3569	0.1	36
Minerals & Miscellaneous	1.0	745	1.6	596	0.4	149
Water	90.8	68418	82.0	30895	99.5	37522
Total Solids, TS	9.2	6967	18.0	37677	0.5	185

Calculation steps

- 1) List the composition of feed streams
- 2) Determine the flowrate of each component in the feed streams
- 3) Calculate component mass flows in retentate stream using retention values, and feed stream component mass flow rates
- 4) Calculate the total mass flow rate of retentate using water as a tie-stream

$$= (\text{sum all non-water component flows in retentate stream}) / (1 - \% \text{ water in retentate} / 100)$$
- 5) Calculate component concentrations in the retentate stream from mass flows
- 6) Calculate component mass flows in permeate stream by difference
- 7) Calculate component concentrations in permeate stream from mass flows

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over evaporator processing retentate stream from skim milk RO plant**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - skim milk evaporation

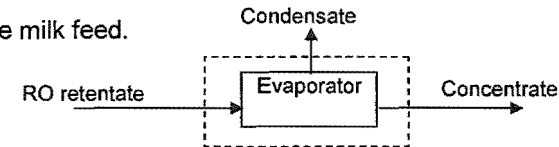
Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

Feed is retentate stream from RO plant processing skim

product composition of Walstra *et al.* (1999). Lactose not enriched - same as whole milk feed.

Evaporator concentrate total solids 52.5 %



	RO retentate		Evap condensate		Evap concentrate	
Mass flow [kg/d]		904246		495183		258356
Mass flow [kg/hr]		37677		24759		12918
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.2	68	0.0	0	0.5	68
Casein	5.4	2038	0.0	0	15.8	2038
Whey protein	1.4	512	0.0	0	4.0	512
Lactose	9.5	3569	0.0	0	27.6	3569
Minerals & Miscellaneous	1.6	596	0.0	0	4.6	596
Water	82.0	30895	100.0	24759	47.5	6136
Total Solids, TS	18.0	6782	0.0	0	52.5	6782

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Calculate component mass flows in concentrate assuming no solids loss in condensate
- 4) Calculate the total mass flow rate of concentrate using water as a tie-stream

$$= (\text{sum all non-water component flows in concentrate}) / (1 - \% \text{ water in concentrate} / 100)$$
- 5) Calculate component concentrations in concentrate stream from mass flows

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over wet blending operation adding cream to skim milk concentrate**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - wet blending with cream

Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

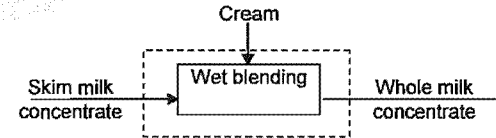
Feed is a skim concentrate from evaporator

Lactose content of lactose powder = 96.5 %

Water content of lactose powder = 3.5 %

Desired concentrate total solids to drier = 50 %

Sufficient cream must be added in order to achieve the desired fat content in the final product



	Evaporator concentrate		Cream		Concentrate to drier	
Mass flow [kg/d]	258356		168000		478027	
Mass flow [kg/hr]	12918		7000		19918	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	0.5	68	40.0	2800	14.4	2868
Casein	15.8	2038	1.6	114	10.8	2151
Whey Protein	4.0	512	0.4	29	2.7	540
Lactose	27.6	3569	2.9	201	18.9	3770
Minerals & miscellaneous	4.6	596	0.6	41	3.2	637
Water	47.5	6136	54.5	3812	49.9	9948
Total Solids, TS	52.5	6782	45.5	3184	50.0	9966

Calculation steps

- 1) List the composition of feed
- 2) List the flowrate of each component in the feed, except for water
- 3) Specify a initial value of required % feed water in evaporator medel
- 4) Calculate the required total mass flow of evaporator concentrate using water as a tie-stream

$$= (\text{sum all non-water component mass flows in evap concentrate milk}) / (1 - \% \text{ water in evap concentrate milk} / 100)$$
- 5) Specify an initial mass flow of cream
- 6) Calculate component mass flows in lactose powder using component concentrations
- 7) Calculate component mass flows in drier concentrate by difference
- 8) Calculate overall mass flow of drier concentrate by difference
- 9) Manipulate evaporator concentrate total solids and cream flow until desired fat content in final powder is achieved and the drier is receiving concentrate feed with 50% total solids

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over spray drier producing high moisture powder, for subsequent drying and lactose dry-blending**

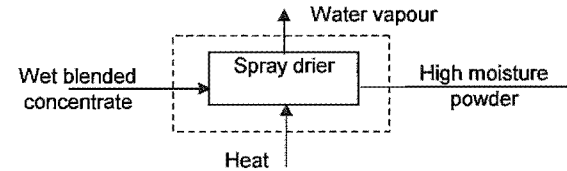
The following calculations show how the mass balance is calculated for Step 9 of the methodology - spray drying of concentrate

Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

Feed is wet blended evaporator concentrate

Assumed powder moisture = 8 %



	Concentrate to drier		Water vapour		High moisture powder	
Mass flow [kg/d]	478027		217956		259989	
Mass flow [kg/hr]	19918		9081		10833	
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]
Fat	14.4	2868	0.0	0	26.5	2868
Casein	10.8	2151	0.0	0	19.9	2151
Whey Protein	2.7	540	0.0	0	5.0	540
Lactose	18.9	3770	0.0	0	34.8	3770
Minerals & miscellaneous	3.2	637	0.0	0	5.9	637
Water	49.9	9948	100.0	9081	8.0	867
Total Solids, TS	50.0	9966	0.0	0	92.0	9966

Calculation steps

- 1) Set component mass flows in concentrated feed stream to be equal to desired whole milk product values, except for water
- 2) Calculate the total mass flow of concentrated feed using water as a tie-stream
= (sum all non-water component mass flows in concentrated feed)/(1-% water in concentrated feed/100)
- 3) Set component concentrations in water vapour equal to zero for all except water
- 4) Calculate component mass flows in high moisture powder stream by difference for all except water
- 5) Calculate the total mass flow rate of high moisture powder using water as a tie-stream
= (sum all non-water component mass flows in high moisture powder stream)/(1-% water in high moisture powder/100)
- 6) Calculate remaining component concentrations in high moisture powder using component mass flows and overall mass flow
- 7) Calculate mass flow of water vapour by difference

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over fluidised bed drier producing low moisture powder, for subsequent lactose dry-blending**

The following calculations show how the mass balance is calculated for Step 9 of the methodology - fluidised drying to high moisture product

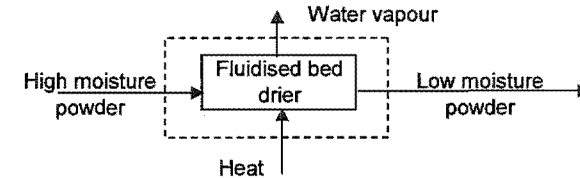
Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

Feed is high moisture whole milk powder from spray drier

Feed moisture = 8 %

Product moisture = 3.5 %



	High moisture powder		Water vapour		Low moisture powder		Desired product (Based on Walstra <i>et al.</i> , 1999)
Mass flow [kg/d]	259989		12124		247865		
Mass flow [kg/hr]	10833		505		10328		
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w
Fat	26.5	2868	0.0	0	27.8	2868	26.0
Casein	19.9	2151	0.0	0	20.8	2151	19.5
Whey Protein	5.0	540	0.0	0	5.2	540	4.9
Lactose	34.8	3770	0.0	0	36.5	3770	38.0
Minerals & miscellaneous	5.9	637	0.0	0	6.2	637	8.1
Water	8.0	867	100.0	505	3.5	361	3.5
Total Solids, TS	92.0	9966	0.0	0	96.5	9966	96.5

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Set component concentrations in water vapour equal to zero for all except water
- 4) Calculate component mass flows in product stream by difference for all except water
- 5) Calculate the total mass flow rate of low moisture powder using water as a tie-stream
 = (sum all non-water component mass flows in low moisture powder stream)/(1-% water in low moisture powder/100)
- 6) Calculate remaining component concentrations in low moisture powder using component mass flows and overall mass flow
- 7) Calculate mass flow of water vapour by difference

APPENDIX C: Case study four**Large scale milk processing : Packed whole milk powder****Component balance over dry blending operation adding lactose to produce whole milk powder product**

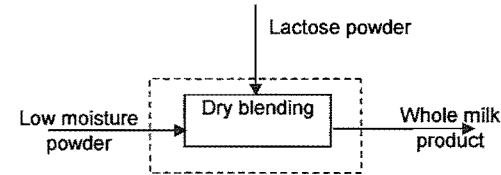
The following calculations show how the mass balance is calculated for Step 9 of the methodology - dry blending with lactose addition

Step 8 calculations repeated using centrifugal separation to achieve low fat feed stream

Assume that 1 day = 24 production hours.

Feed is low moisture whole milk powder from fluidised bed drier

Final product moisture =	3.5 %
Fat content of lactose powder =	0 %
Casein content of lactose powder =	0 %
Whey protein content of lactose powder =	0 %
Lactose content of lactose powder =	96.5 %
Minerals content of lactose powder =	0 %
Water content of lactose powder =	3.5 %



	Low moisture powder		Lactose powder		Final product		Desired product (Based on Walstra <i>et al.</i> , 1999)
Mass flow [kg/d]	247865		16800		266667		
Mass flow [kg/hr]	10328		700		11028		
	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w	[kg/hr]	% w/w
Fat	27.8	2868	0.0	0	26.0	2868	26.0
Casein	20.8	2151	0.0	0	19.5	2151	19.5
Whey Protein	5.2	540	0.0	0	4.9	540	4.9
Lactose	36.5	3770	96.5	676	40.3	4445	38.0
Minerals & miscellaneous	6.2	637	0.0	0	5.8	637	8.1
Water	3.5	361	3.5	25	3.5	386	3.5
Total Solids, TS	96.5	9966	96.5	676	96.5	10642	96.5

Calculation steps

- 1) List the composition of feed
- 2) Determine the flowrate of each component in the feed
- 3) Specify an initial mass flow of lactose powder
- 4) Calculate component mass flows in lactose powder stream
- 5) Calculate overall and component mass flows in final product by difference
- 6) Calculate component concentrations in final product using component mass flows and overall mass flow
- 7) Manipulate the mass flow of lactose powder until desired powder composition is achieved.
- 8) Review cream addition rate in concentrate wet blending and manipulate if necessary to achieve the desired powder composition

Minerals content of powder is low so lactose content elevated to compensate. Final product is still considered to meet spec requirements